

Tevatron: Studying pp Collisions at the highest Energy

Lecture I

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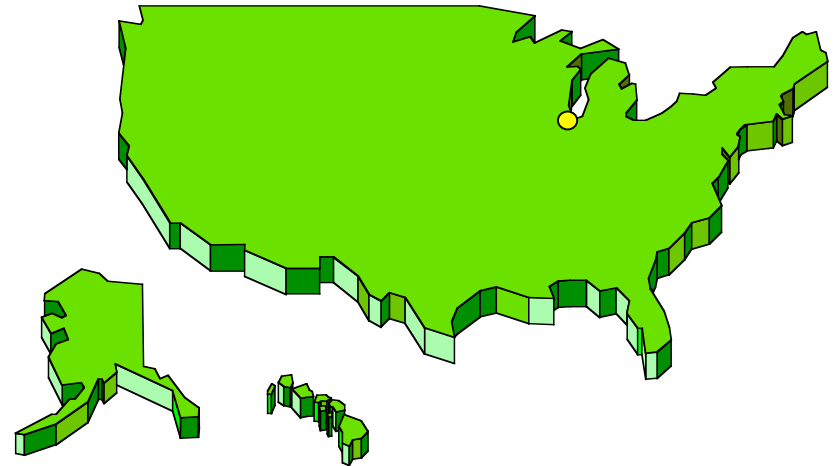
CERN, May 15-19th 2006

Outline

- Lecture I
 - The Tevatron, CDF and DØ
 - Production Cross Section Measurements
- Lecture II
 - The Top Quark and the Higgs Boson
 - jet energy scale and b-tagging
- Lecture III
 - B_s mixing and $B_s \rightarrow \mu\mu$ rare decay
 - Vertex resolution and particle identification
- Lecture IV
 - Supersymmetry and High Mass Dilepton/Diphoton
 - Missing E_T

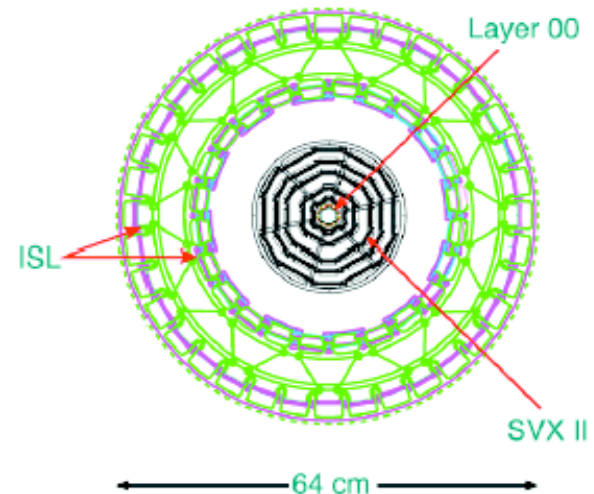
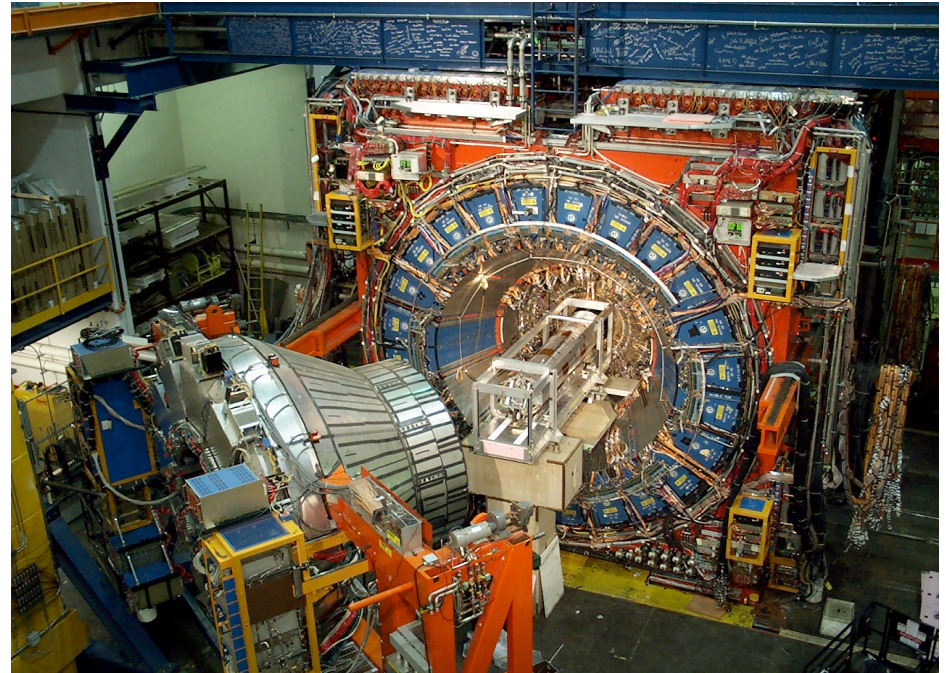
The Tevatron

- pp collider:
 - Beam energy: 980 GeV
 - $\sqrt{s}=1.96$ TeV
 - 36 bunches:
 - Time between bunches $\Delta t=396$ ns
 - Inst. $L=1.8 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
 - By now: $\int L dt = 1.6 \text{ fb}^{-1}$
- Main challenges:
 - Anti-proton production and storage:
 - Stochastic and electron cooling
 - Irregular failures:
 - Kicker prefires
 - Quenches

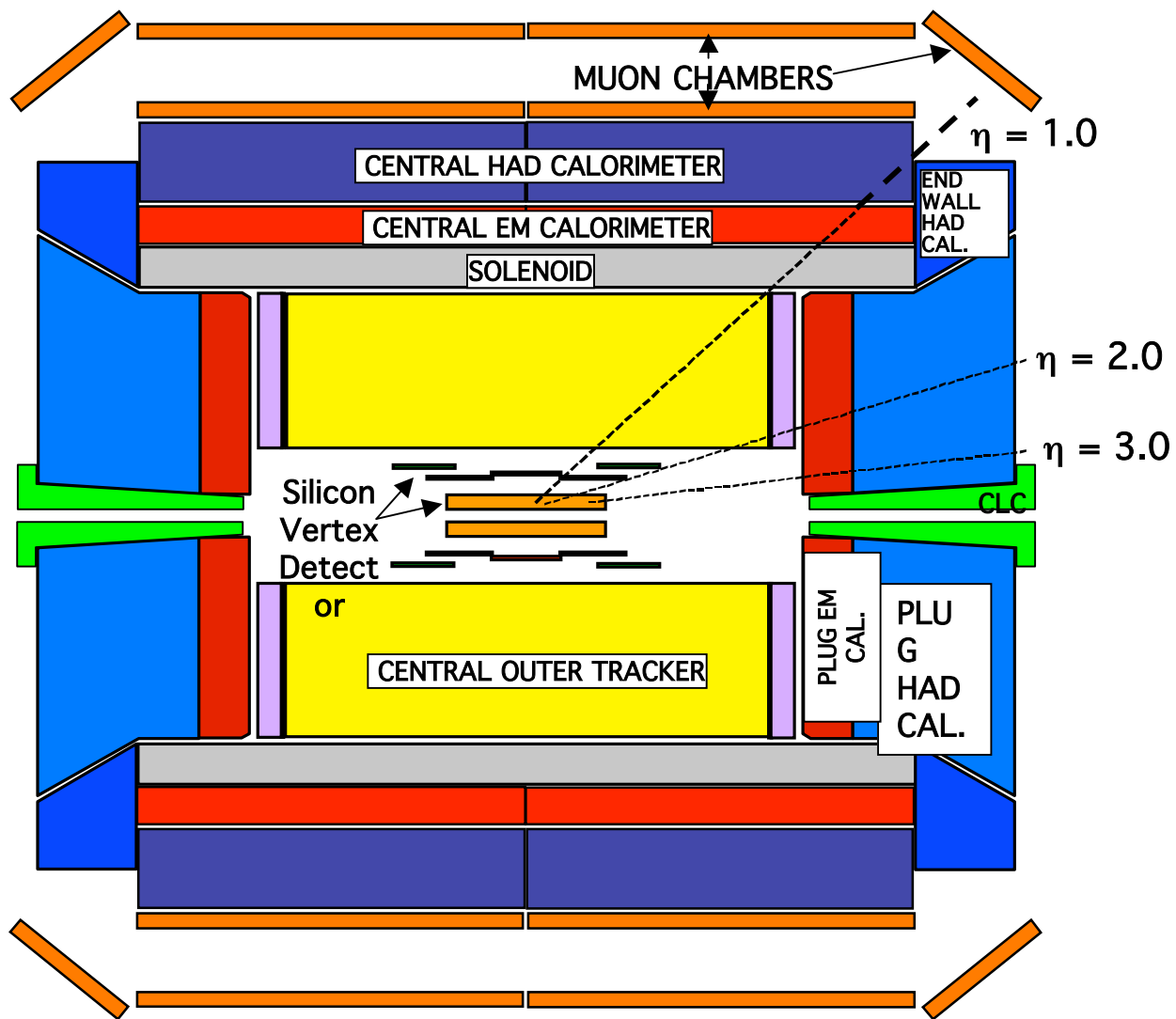


CDF

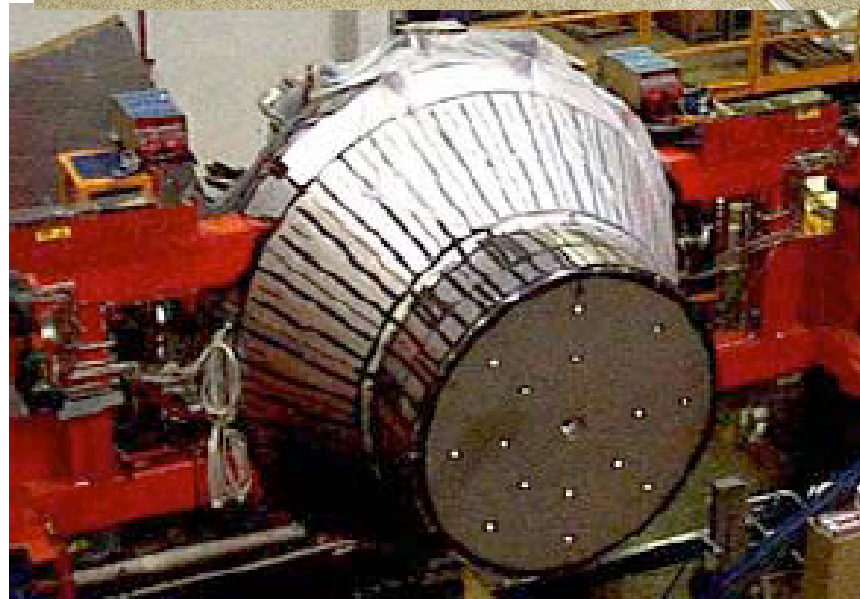
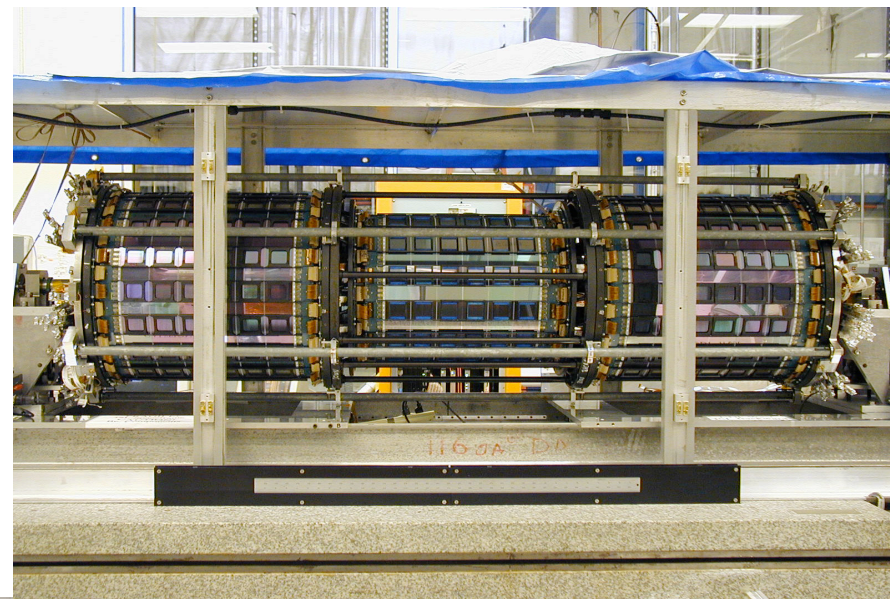
- Core detector operates since 1985:
 - Central Calorimeters
 - Central muon chambers
- Major upgrades for Run II:
 - Drift chamber: COT
 - Silicon: SVX, ISL, L00
 - 8 layers
 - 700k readout channels
 - 6 m²
 - material: 15% X_0
 - Forward calorimeters
 - Forward muon system
 - Improved central too
 - Time-of-flight
 - Preshower detector
 - Timing in EM calorimeter
 - Trigger and DAQ



CDF



Some new CDF Subdetectors

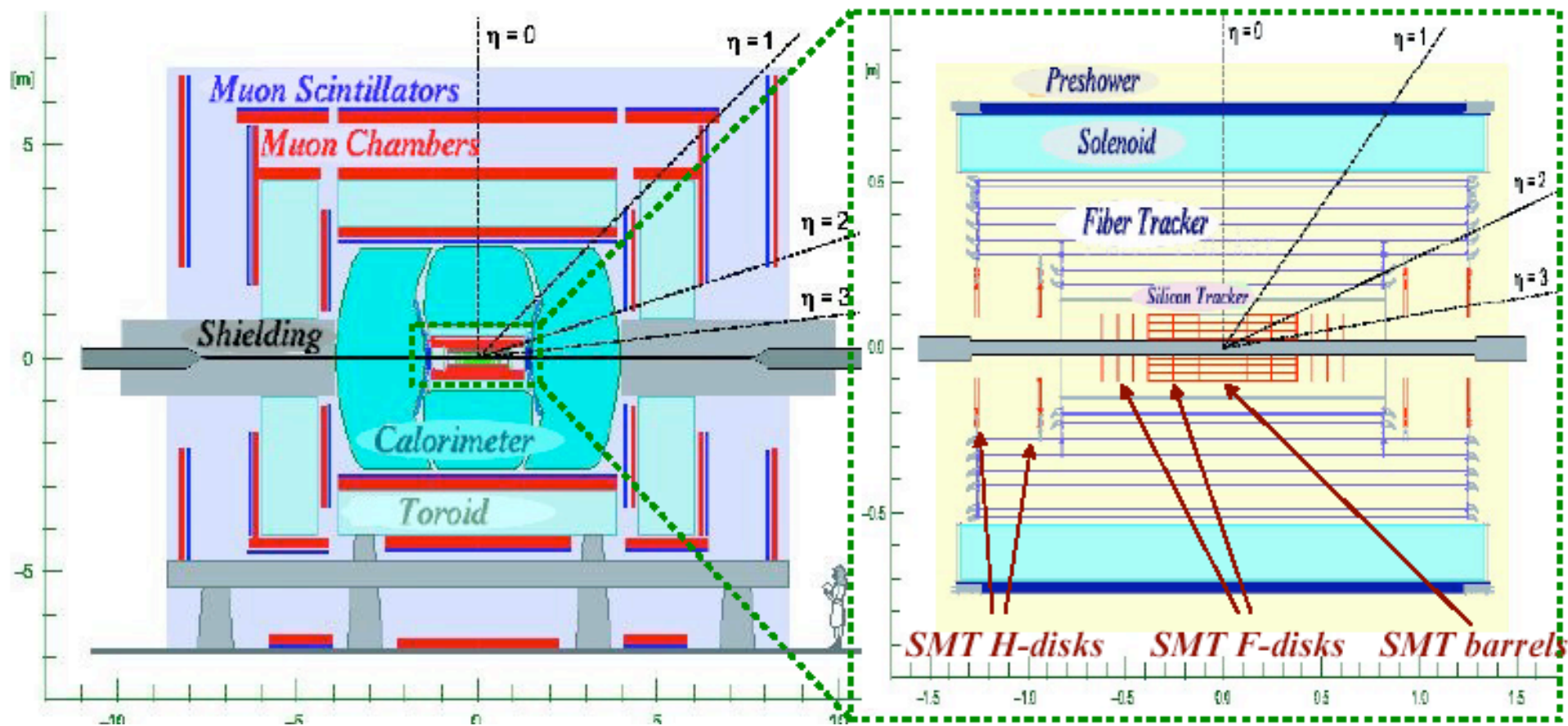


DØ Detector

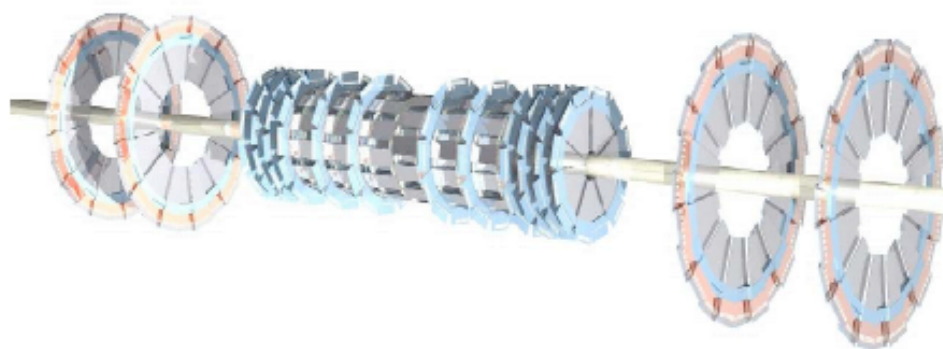
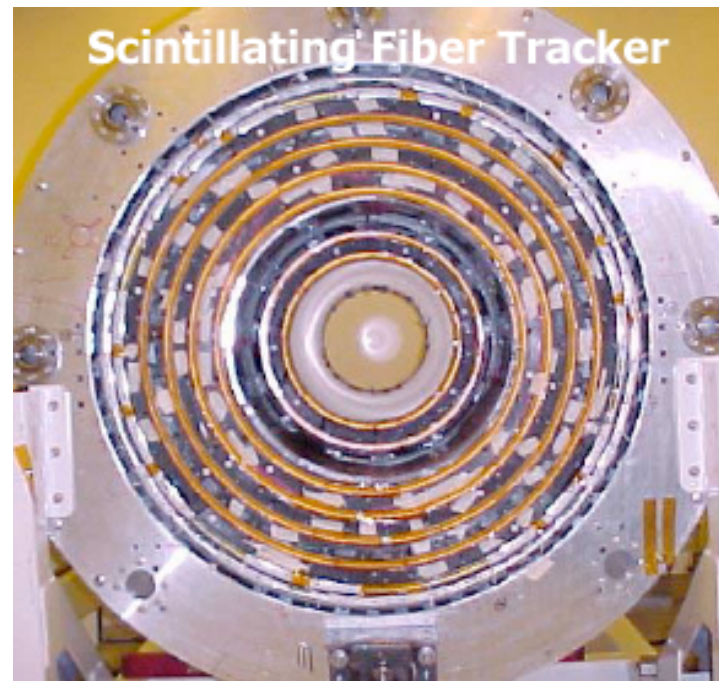
- Retained from Run I
 - Excellent muon coverage
 - Compact high granularity LAr calorimeter
- New for run 2:
 - A magnet!
 - Silicon detector
 - Fiber tracker
 - Trigger
 - Readout
 - Forward roman pots



DØ Detector



Pictures of DØ Subdetectors

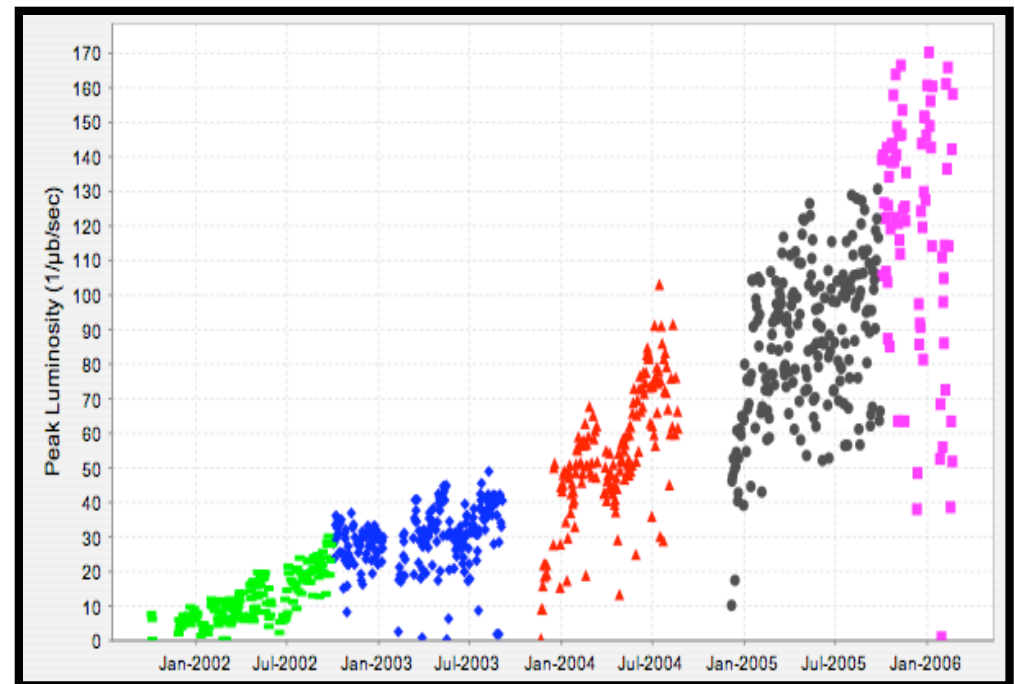


Tevatron Luminosity

Congratulations Fermilab!

Fermilab has set a world record for peak luminosity of a hadron collider!

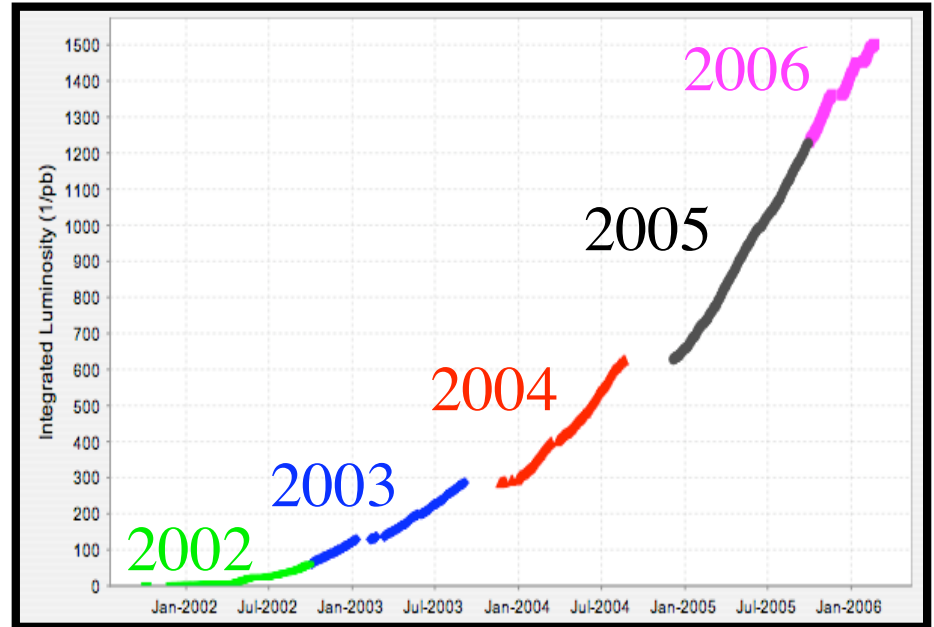
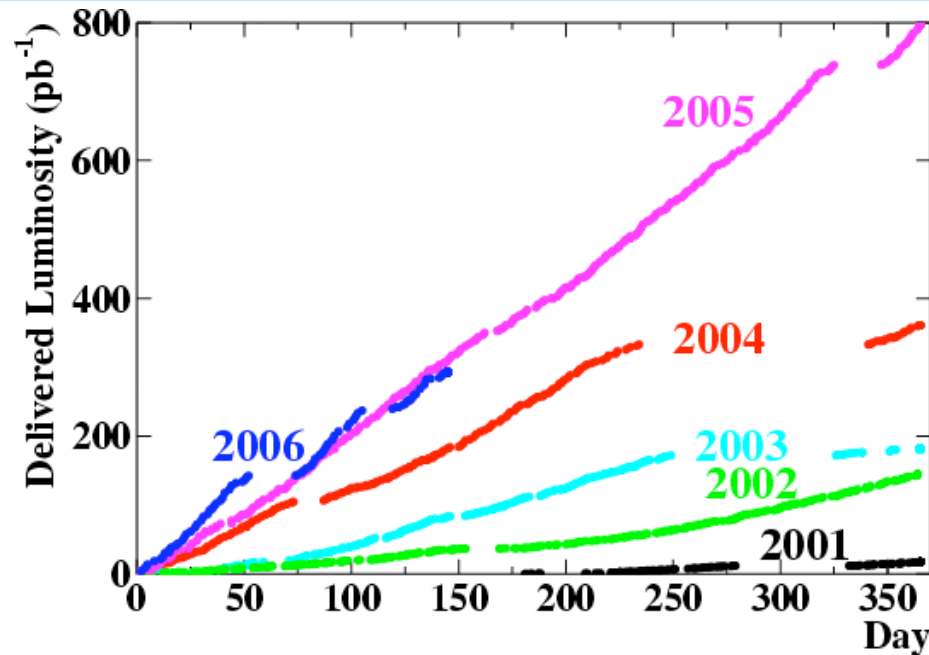
Operations established store 4431 at 9:11 a.m. yesterday, October 4, with an initial luminosity, or brightness, of $141\text{E}30\text{ cm}^{-2}\text{sec}^{-1}$. This record exceeds the previous Tevatron record by almost 8 percent, and it exceeds the world record for peak luminosity of a hadron collider achieved 23 years ago by the ISR proton-proton collider at CERN. The ISR achieved a peak luminosity of $140\text{E}30\text{ cm}^{-2}\text{sec}^{-1}$ at a collision energy of 62 GeV. The Tevatron produces collisions between protons and antiprotons at a collision energy of 1960 GeV. The peak luminosity of the Tevatron has greatly increased since Fermilab began Run II in March 2001, and Fermilab expects to improve the Tevatron peak luminosity even further.



Tevatron Has Another Peak Luminosity Record in 2006

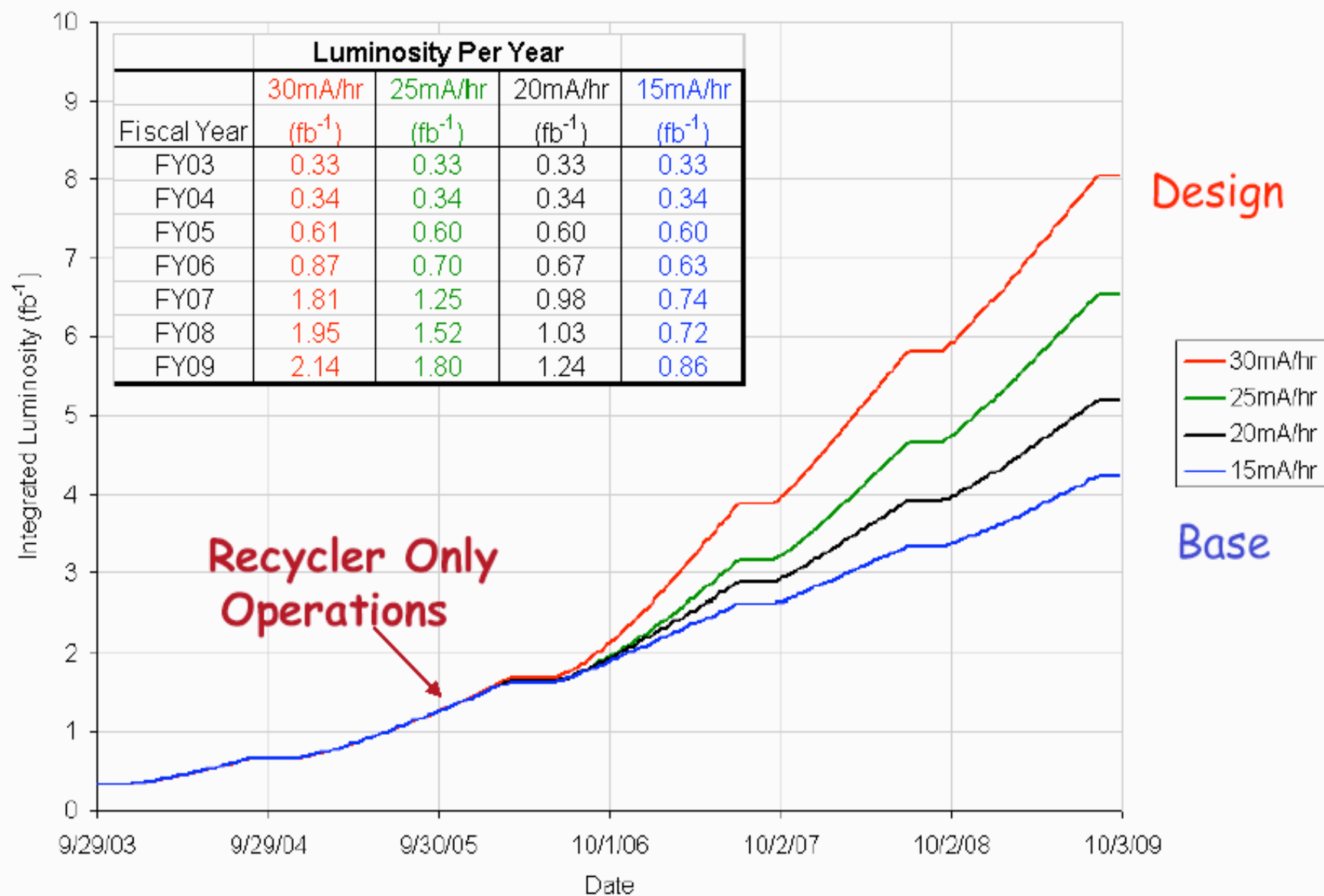
The Tevatron collider set a new peak luminosity record at 3:28 this morning, January 6. Store 4581 reached $171\text{E}30\text{ cm}^{-2}\text{sec}^{-1}$. Congratulations.

Tevatron Performance

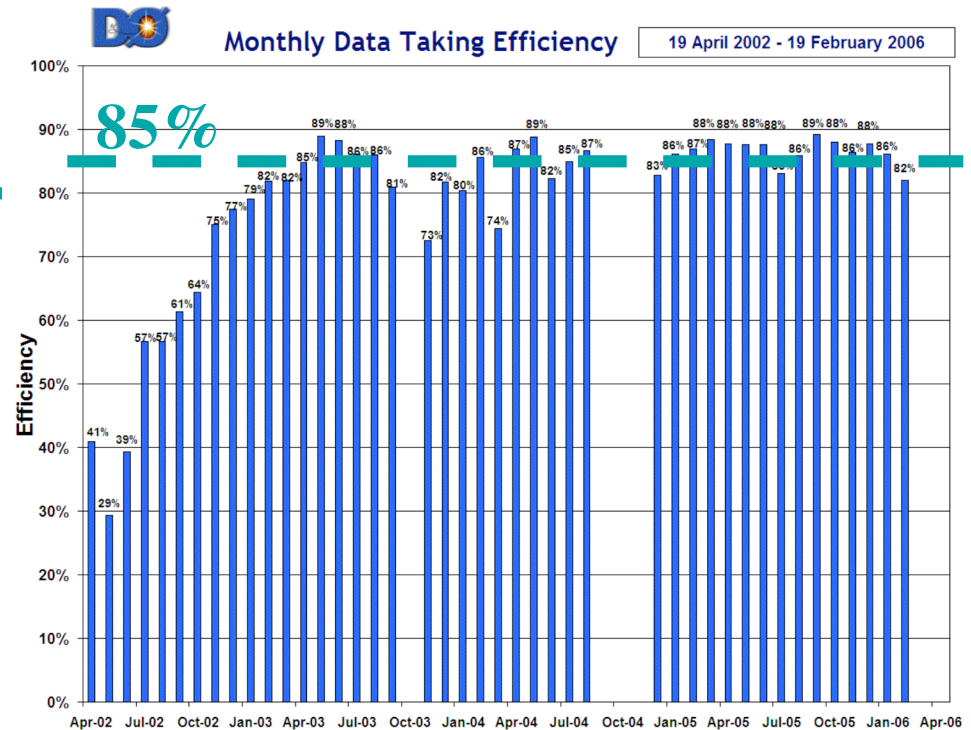
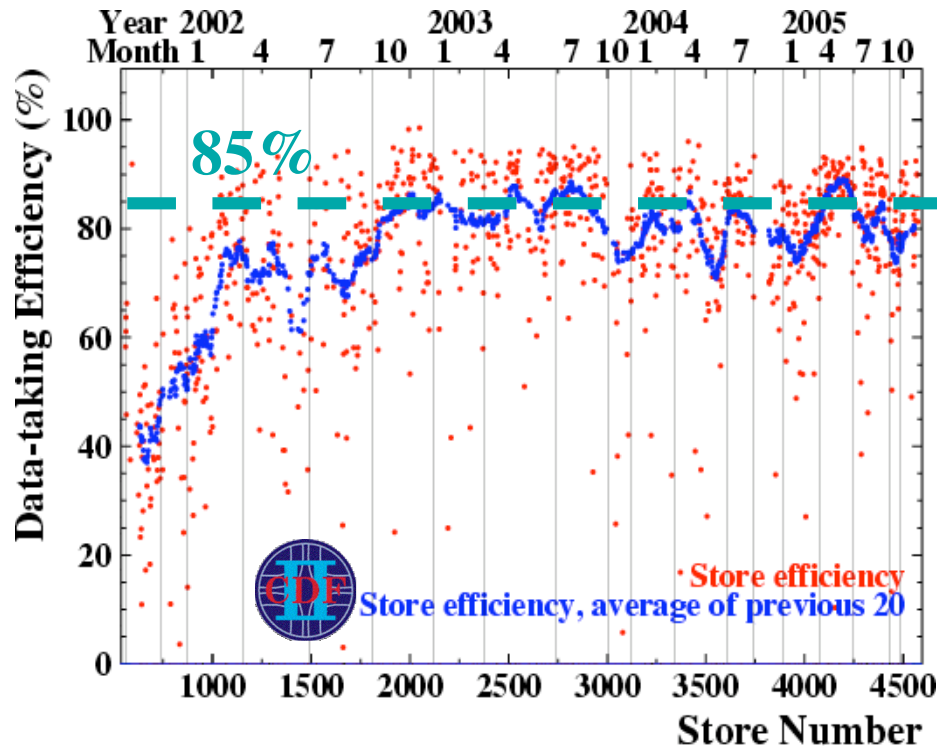


- Integrated luminosity more than 1.5 fb^{-1} by now
 - First years were difficult
 - March'01-March'02 used for commissioning of detectors
 - Physics started in March'02
 - Luminosity doubles every year
- Currently in shutdown until early June:
 - install new silicon L0 in D0

Tevatron: Future



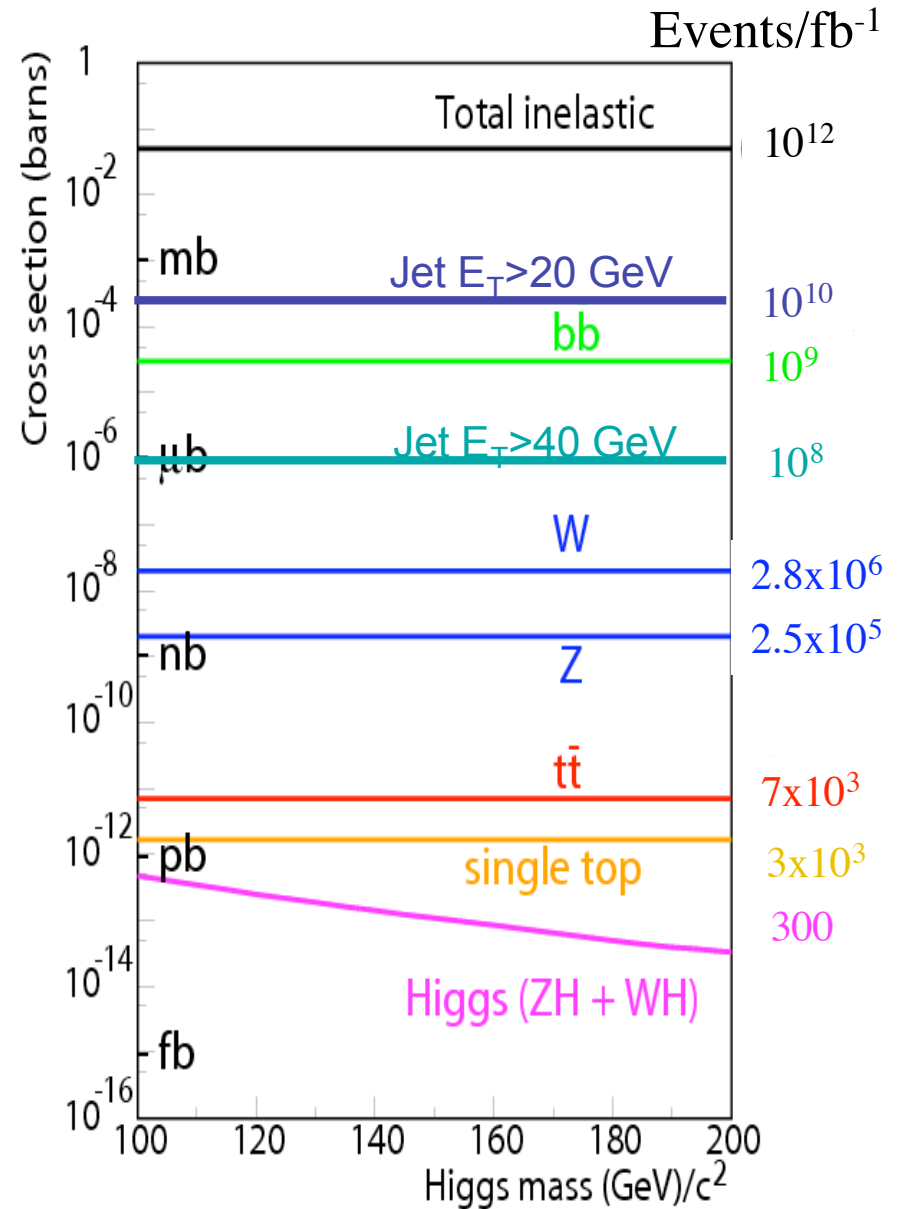
Detector Performances



- Data taking efficiency about 85%
- All components working very well:
 - 93% of Silicon detector operates, 82-96% working well
 - Expected to last up to 8 fb^{-1}

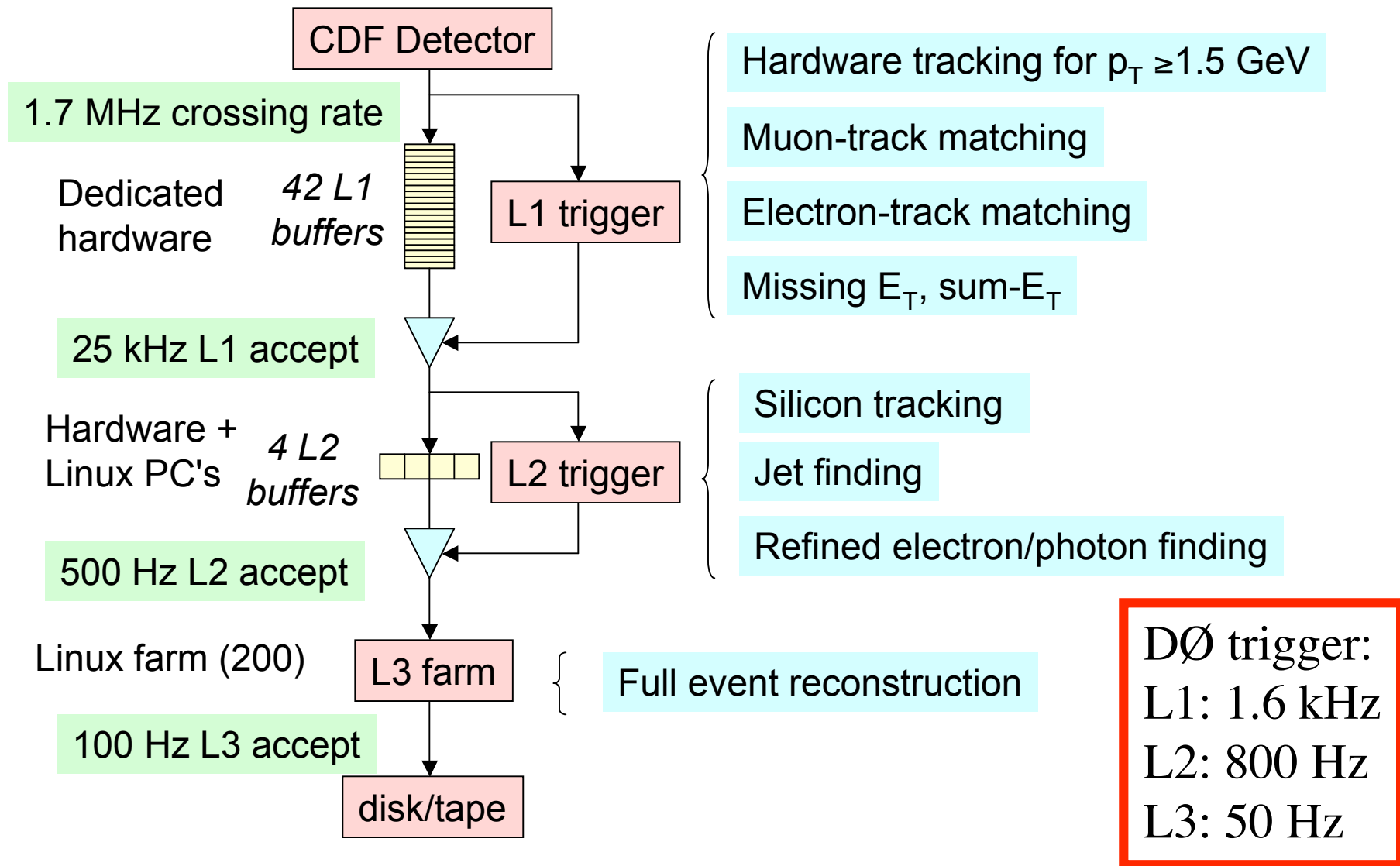
Processes and Cross Sections

- Cross section:
 - Total inelastic cross section is huge
 - Used to measure luminosity
- Rates at e.g. $L=1 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$:
 - Total inelastic: 70 MHz
 - bb : 42 kHz
 - Jets with $E_T > 40 \text{ GeV}$: 300 Hz
 - W : 3 Hz
 - Top: 0.0007 Hz
- Trigger needs to select the interesting events
 - Mostly fighting generic jets!



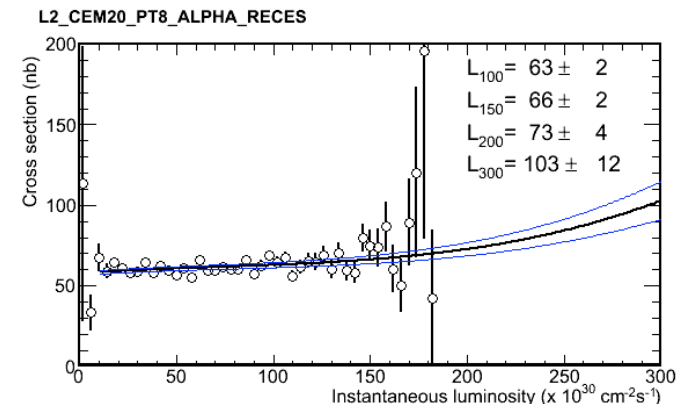
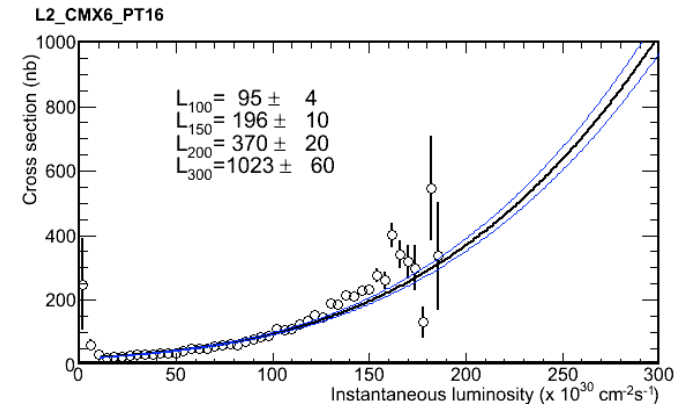
Triggering at hadron colliders

The trigger is the key at hadron colliders



Typical Triggers and their Usage

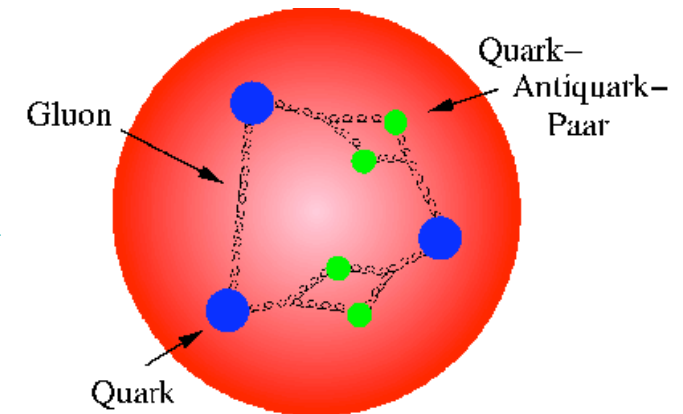
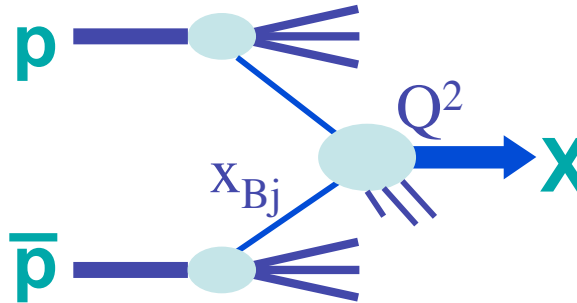
- Unprescaled triggers for primary physics goals
- Examples:
 - Inclusive electrons, muons $p_T > 20$ GeV:
 - W, Z, top, WH, single top, SUSY, Z', Z''
 - Dileptons, $p_T > 4$ GeV:
 - SUSY
 - Lepton+tau, $p_T > 8$ GeV:
 - MSSM Higgs, SUSY, Z
 - Also have tau+MET: $W \rightarrow \tau \nu$
 - Jets, $E_T > 100$ GeV
 - Jet cross section
 - Monojet search
 - Lepton and b-jet fake rates
 - Photons, $E_T > 25$ GeV:
 - Photon cross sections
 - Jet energy scale
 - Searches (GMSB SUSY)
 - Missing $E_T > 45$ GeV
 - SUSY
 - $ZH \rightarrow \nu \nu b \bar{b}$
- Prescale triggers because:
 - Not possible to keep at highest luminosity
 - Needed for monitoring
- Examples:
 - Jets at $E_T > 20, 50, 70$ GeV
 - Inclusive leptons > 8 GeV
 - B-physics triggers



The Proton

- It's complicated:

- Valence quarks
- Gluons
- Sea quarks

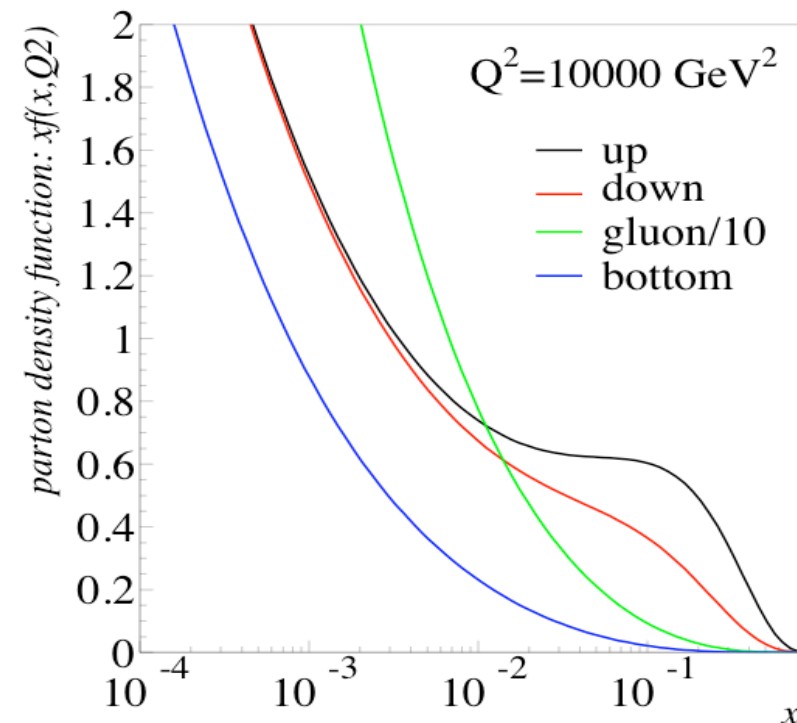


- Exact mixture depends on:

- Q^2 : $\sim(M^2 + p_T^2)$
- x_{Bj} : fractional momentum carried by parton

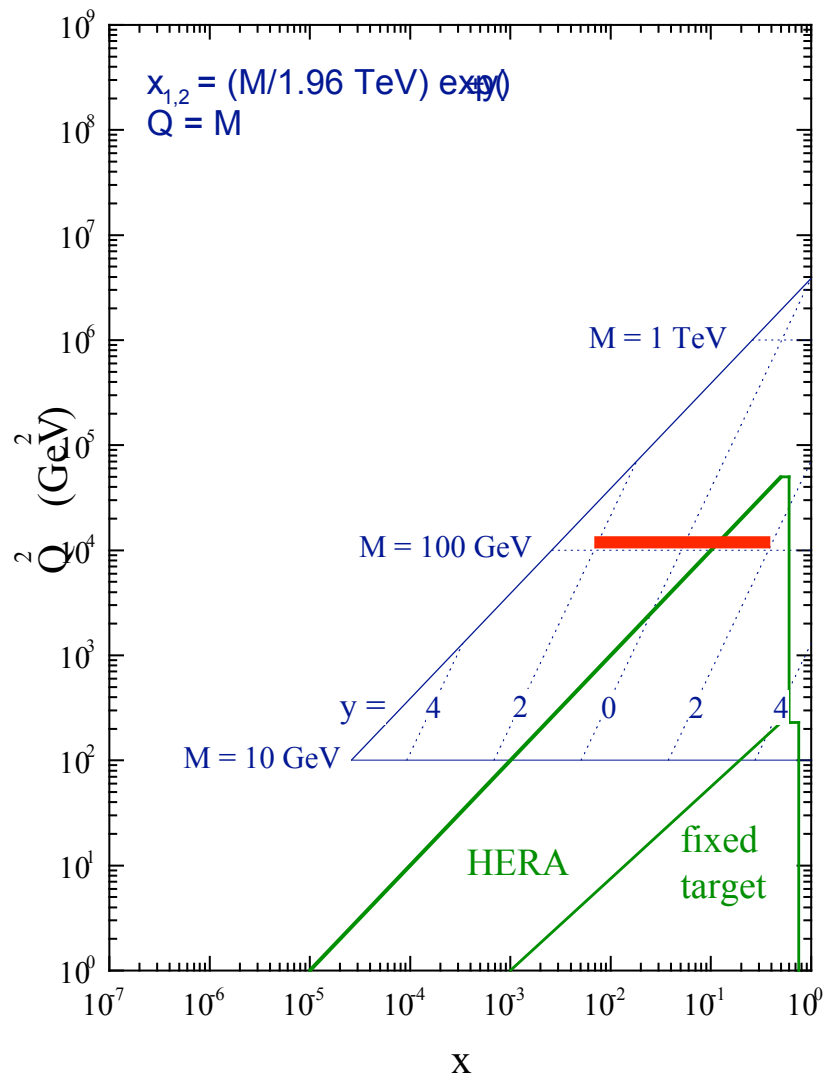
- Hard scatter process:

$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

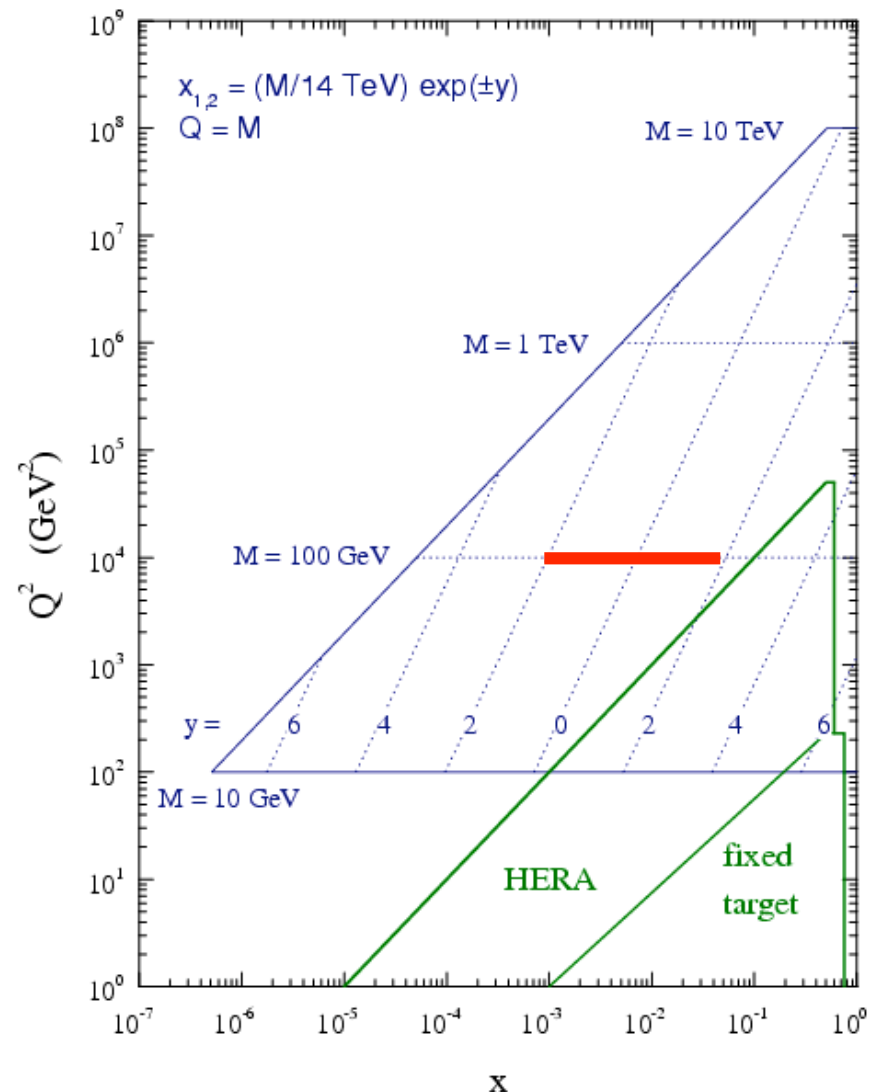


Parton Kinematics

Tevatron parton kinematics



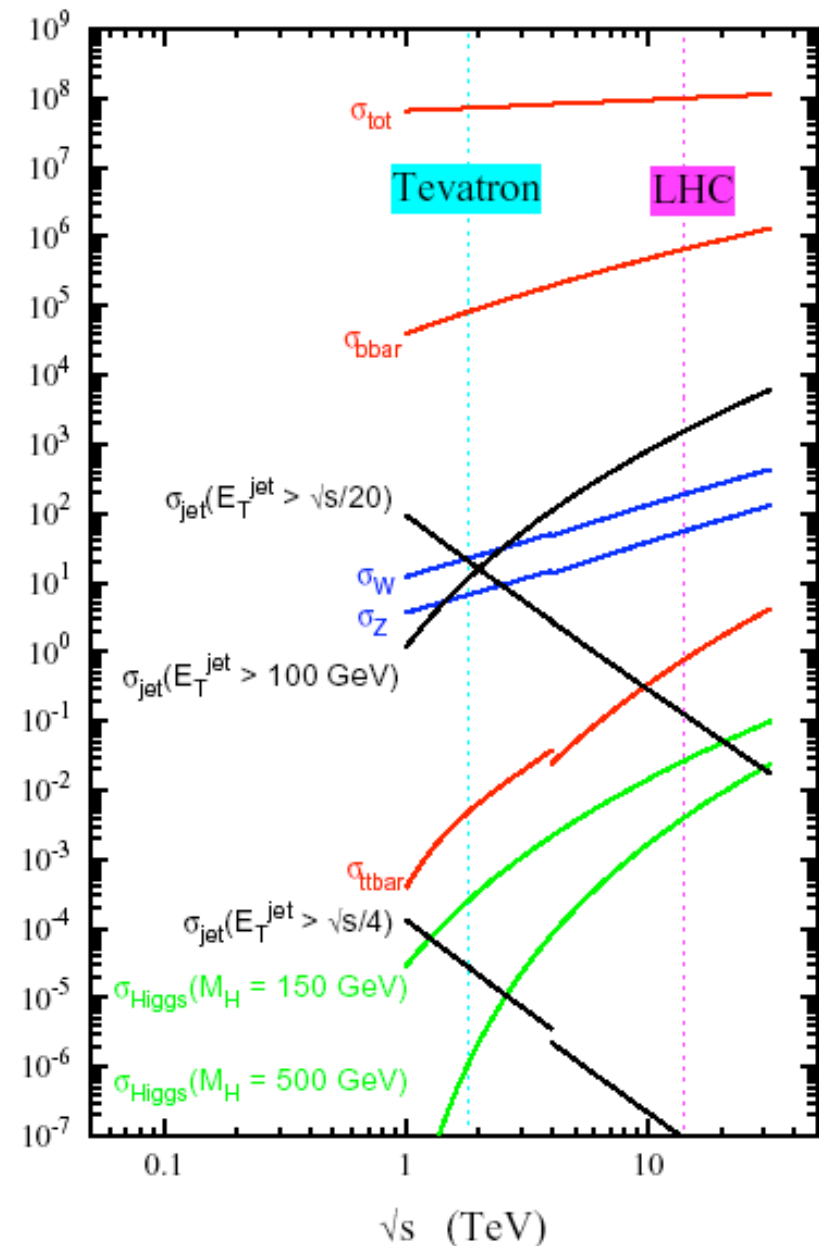
LHC parton kinematics



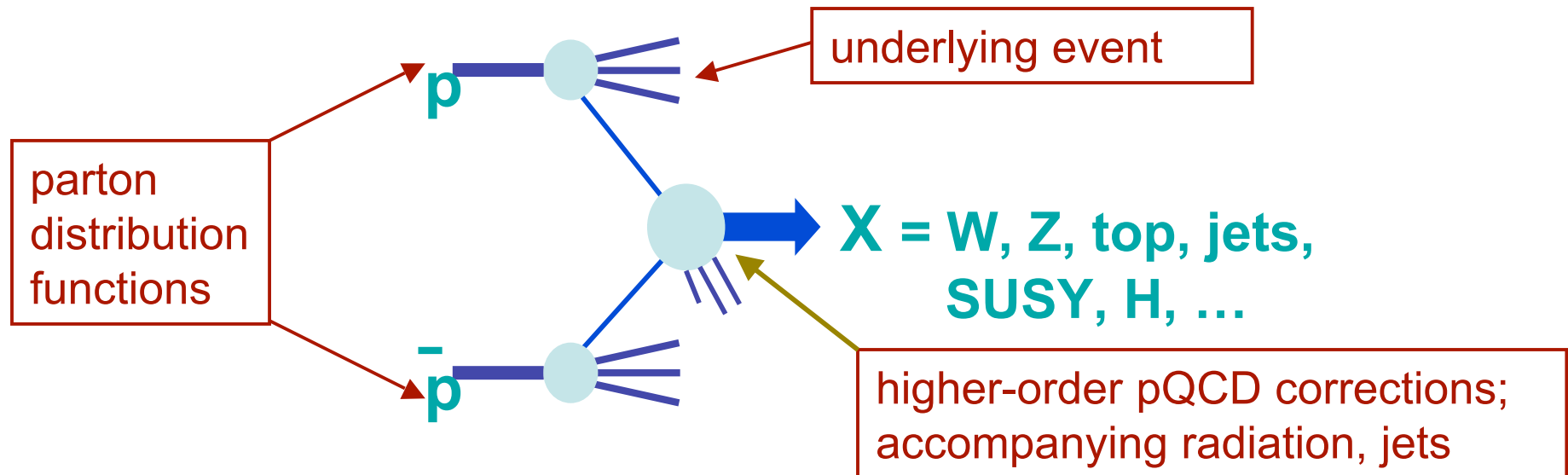
- For **M=100 GeV**: probe 10 times higher x at Tevatron than LHC

Tevatron vs LHC

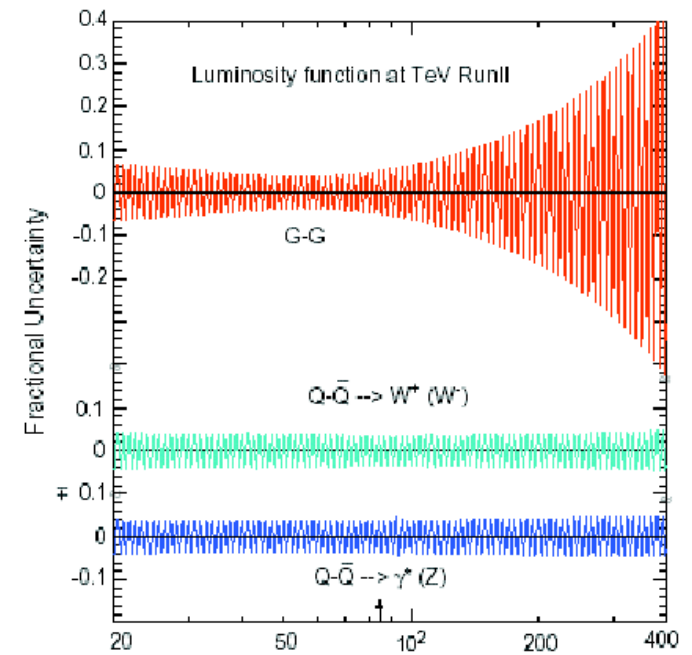
- Compare to LHC
 - Cross sections of heavy objects rise much faster, e.g.
 - top cross section
 - Jet cross section $E_T > 100$ GeV
- Relative importance of processes changes
 - Jet background to W's and Z's
 - W background to top
 - backgrounds to Higgs



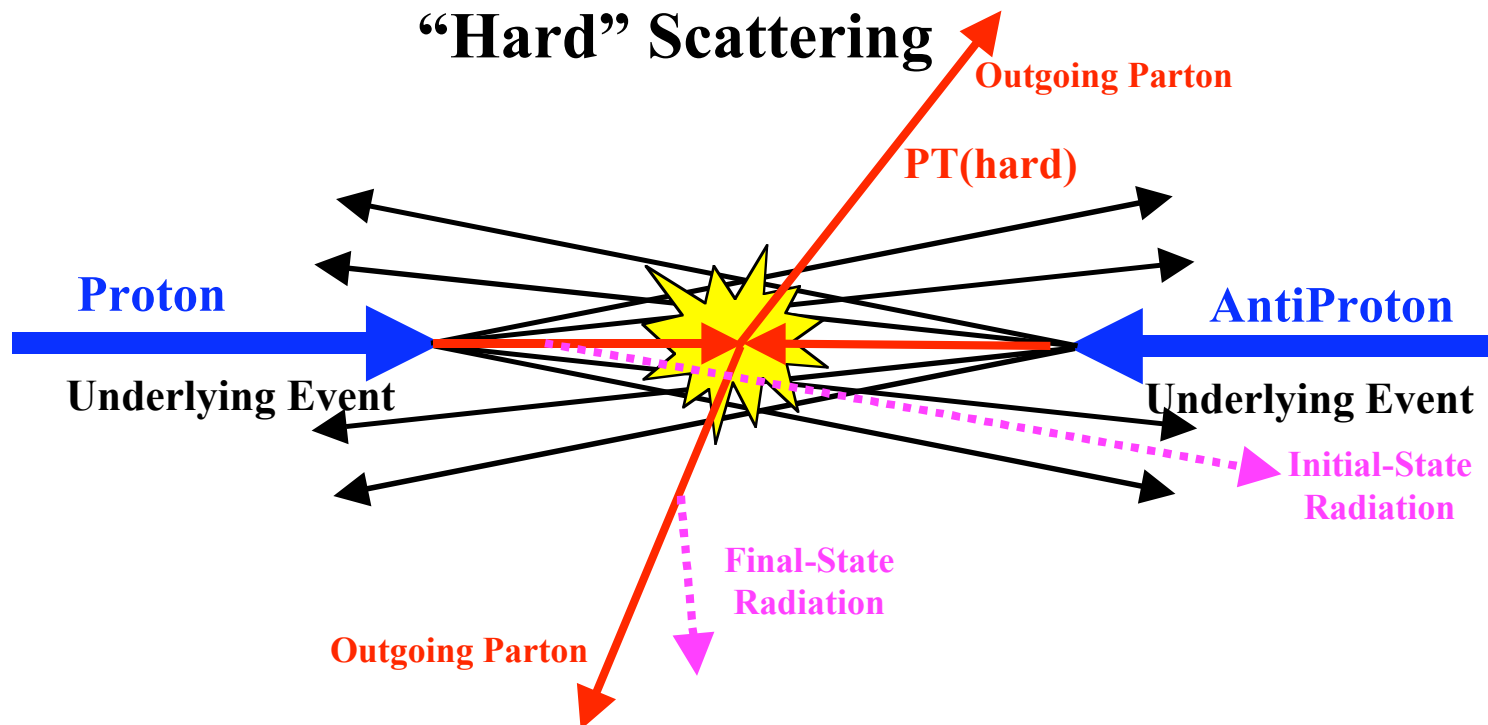
The Proton is Messy



- We don't know
 - which partons hit each other
 - What their momentum was
 - What the other partons did
- We know roughly: 2-30%
 - The parton content of the proton
 - The cross sections of processes



Every Event is Complicated



- “Underlying event”:
 - Initial state radiation
 - Interactions of other partons in proton
- Many forward particles escape detection
 - Transverse momentum ~ 0
 - Longitudinal momentum $\gg 0$

Kinematic Constraints and Variables

- **Transverse momentum, p_T**
 - Particles that escape detection (0) have $p_T=0$
 - Visible transverse momentum $=0$
 - Very useful variable!
- Longitudinal momentum and energy, p_z and E
 - Particles that escape detection have large p_z
 - Visible p_z is not conserved
 - Not so useful variable
- Angle:
 - Polar angle θ is not Lorentz invariant
 - Rapidity: y
 - **Pseudorapidity: η**

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

For $M=0$

$$y = \eta = -\ln\left(\tan \frac{\theta}{2}\right)$$

Standard Model

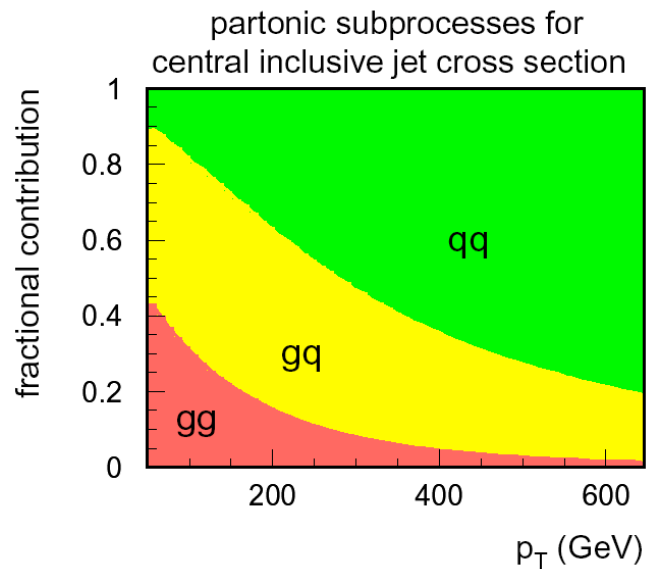
Processes and Cross Sections

- Jets
- W's and Z's
- WW and diphotons

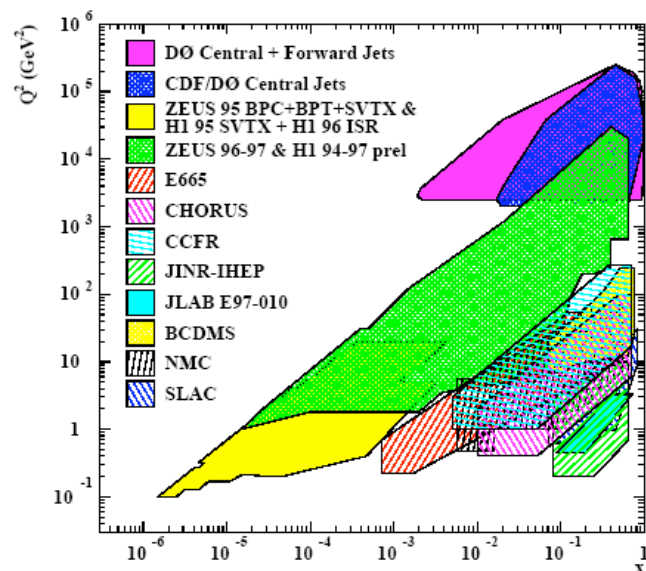
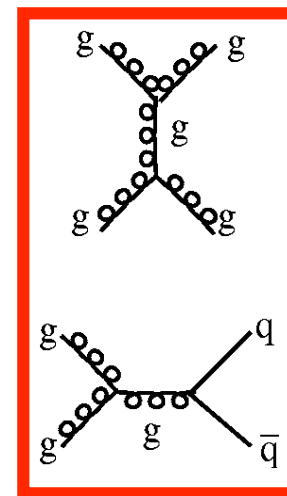
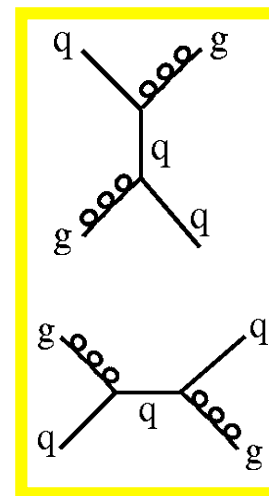
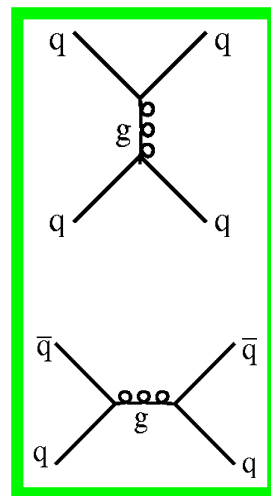
Why Measure Cross Sections?

- They test QCD calculations
 - They help us to find out content of proton:
 - Gluons, light quarks, c- and b-quarks
 - A cross section that disagrees with theoretical prediction could be first sign of new physics:
 - E.g. quark substructure (highest jet E_T)
- They force us to understand the detector
- Noone believes us anything without us showing we can measure cross sections

Jet Cross Sections



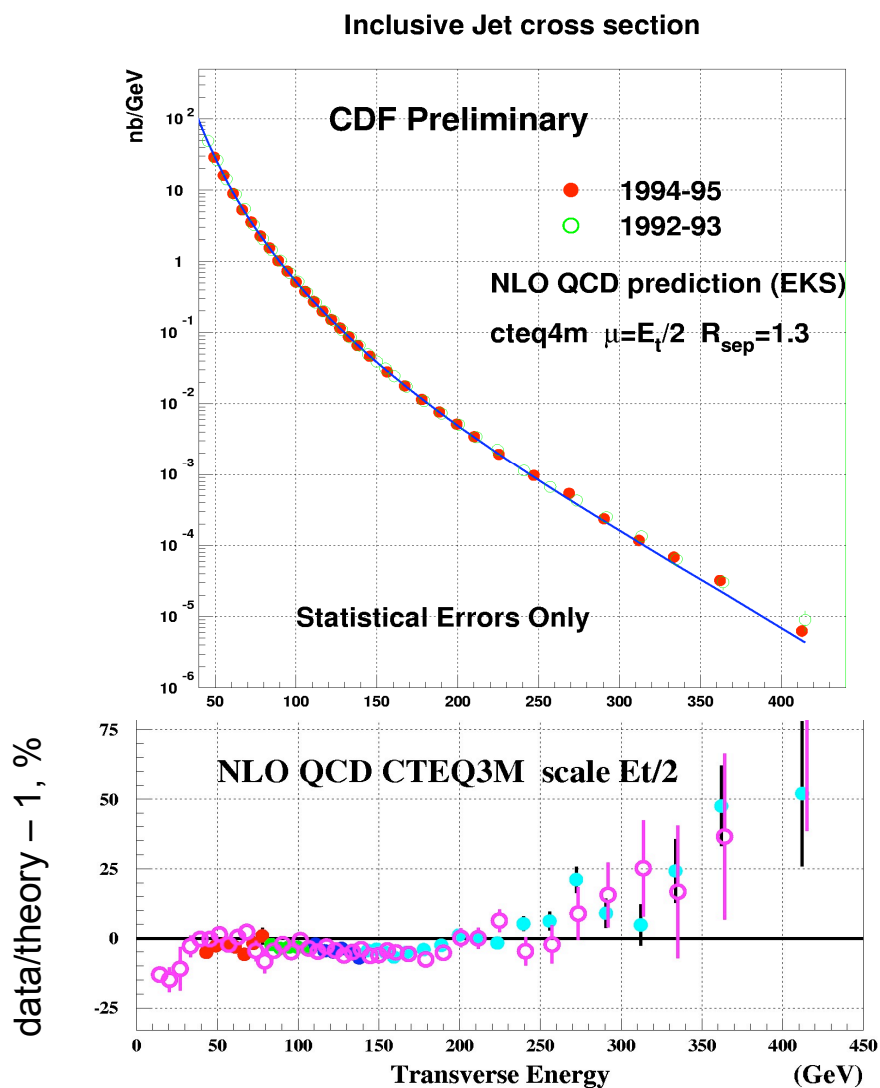
- Inclusive jets: processes qq, qg, gg



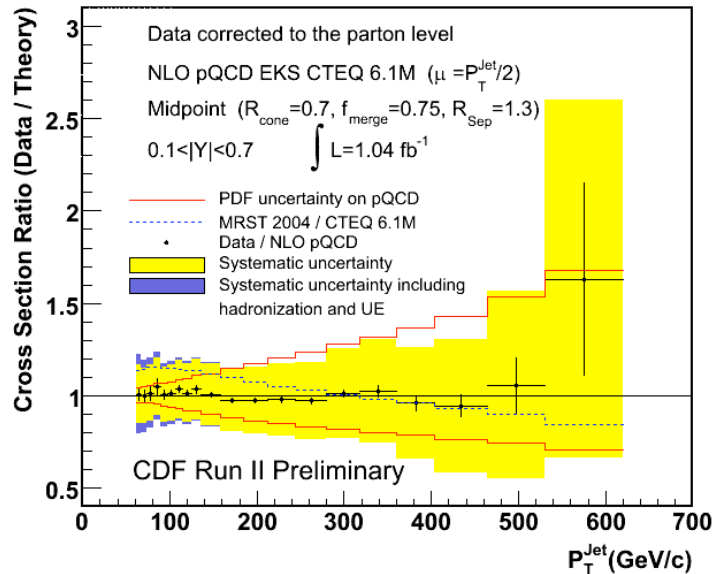
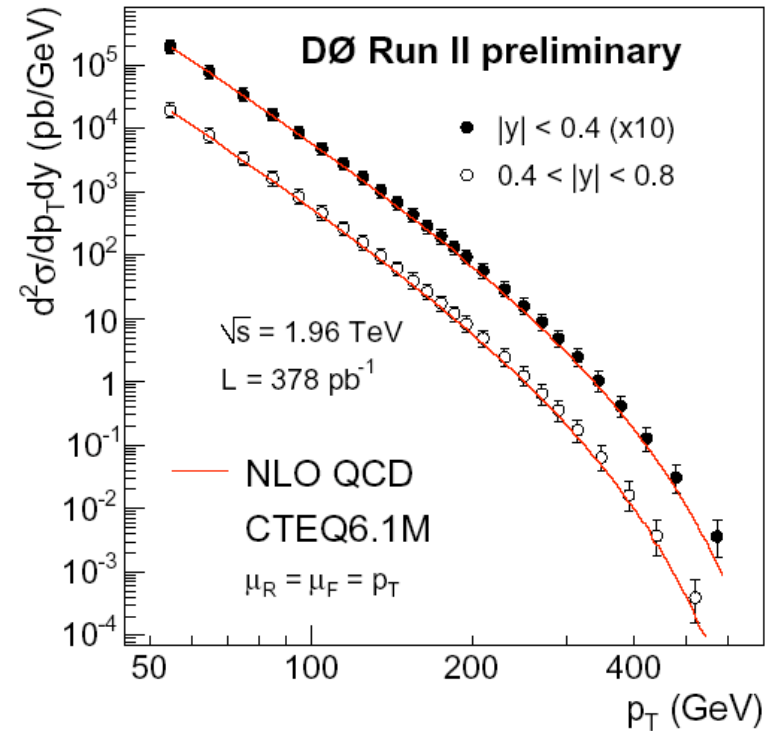
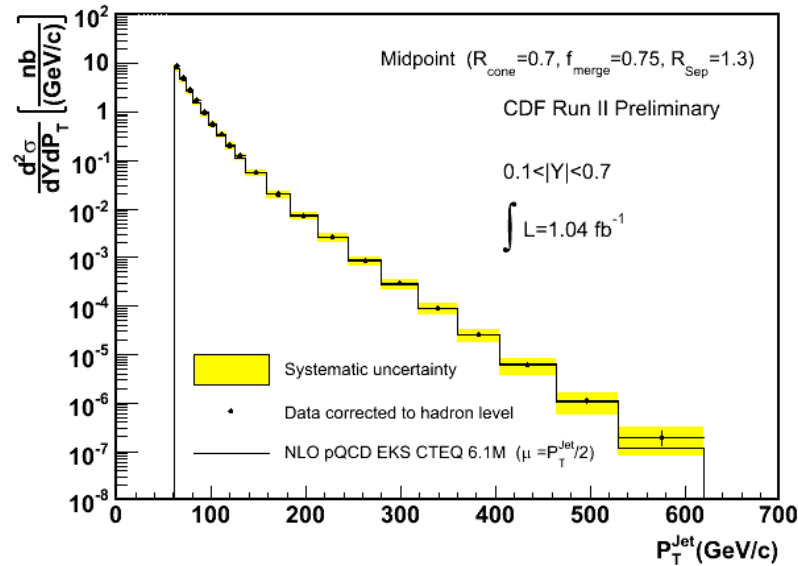
- Measure at highest Q^2 and x
 - Testing new grounds
 - High Q^2
 - new physics at TeV scale?

Jet Cross Section History

- Run I:
 - Excess at high ET
 - Could signal quark substructure!
- Since run I:
 - Revision of parton density functions
 - Different jet algorithms
 - MidPoint
 - k_T
 - Both are infrared safe

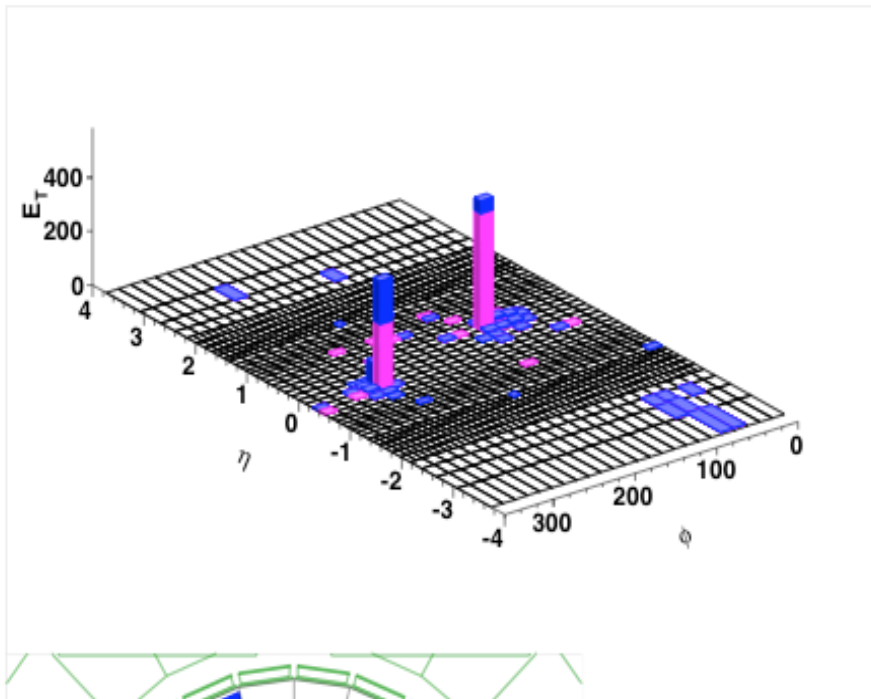


Jet Cross Sections in Run II



- Excellent agreement with QCD calculation over 8 orders of magnitude!

Highest Mass Dijet Event: $M=1.4$ TeV



CDF Run II Preliminary

Jet E_{T1} = 666 GeV (corr)

583 GeV (raw)

η_{11} = 0.31 (detector)

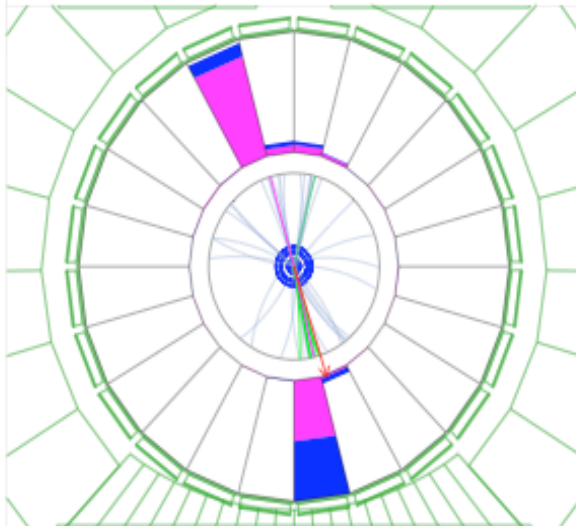
0.43 (corr z)

Jet E_{T2} = 633 GeV (corr)

546 GeV (raw)

η_{21} = -0.30 (detector)

-0.19 (corr z)



Run 152507

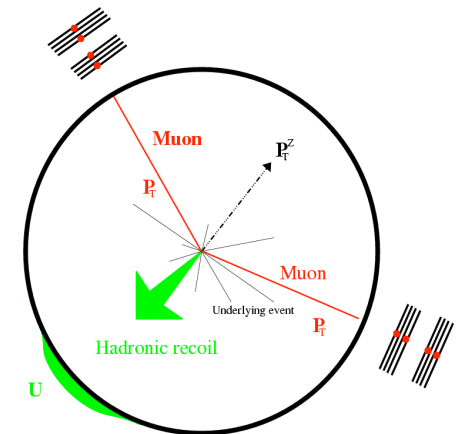
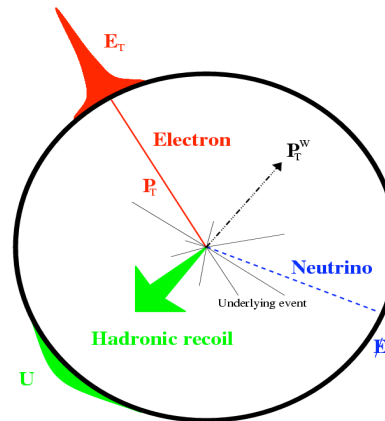
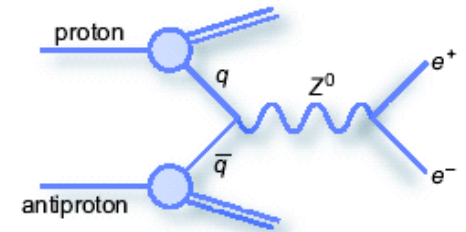
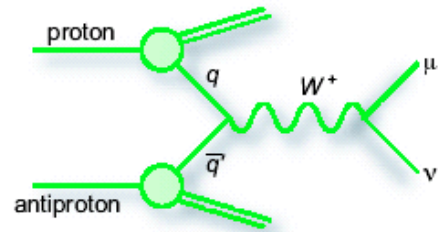
Event 1222318

DiJet Mass = 1364 GeV (corr)

z vertex = -25 cm

W and Z Bosons

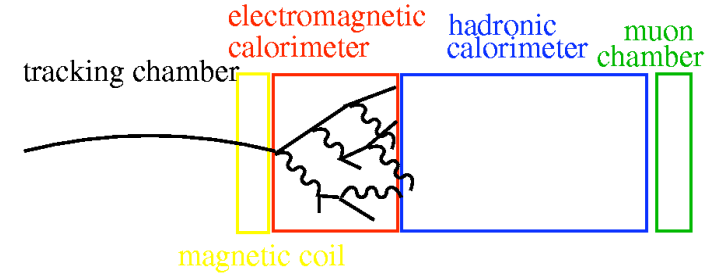
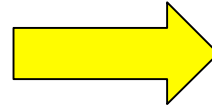
- Focus on leptonic decays:
 - Hadronic decays impossible due to enormous QCD dijet background
- Selection:
 - Z:
 - Two leptons $E_T > 20$ GeV
 - Electron, muon, tau
 - W:
 - One lepton $E_T > 20$ GeV
 - Large imbalance in transverse momentum
 - Missing $E_T > 20$ GeV
 - Signature of undetected particle (neutrino)
- Excellent calibration signal for many purposes:
 - Electron energy scale
 - Track momentum scale
 - Lepton ID and trigger efficiencies
 - Missing ET resolution
 - Luminosity ...



Lepton Identification

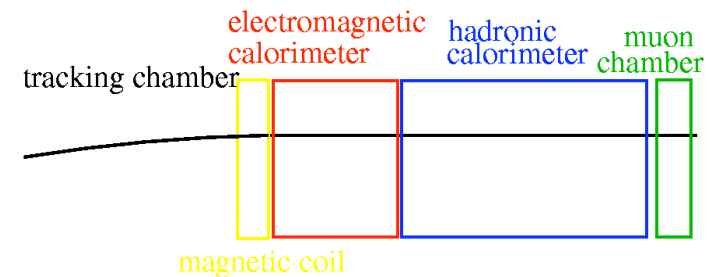
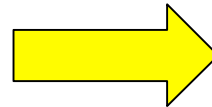
- Electrons:

- compact electromagnetic cluster in calorimeter
- Matched to track



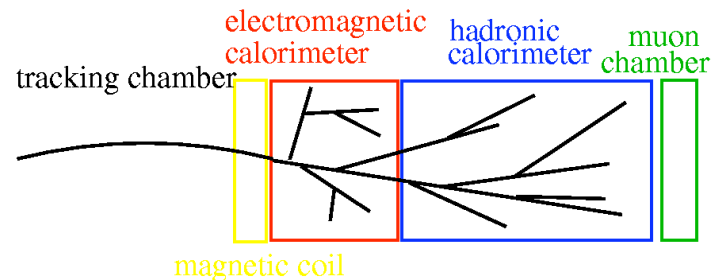
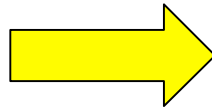
- Muons:

- Track in the muon chambers
- Matched to track



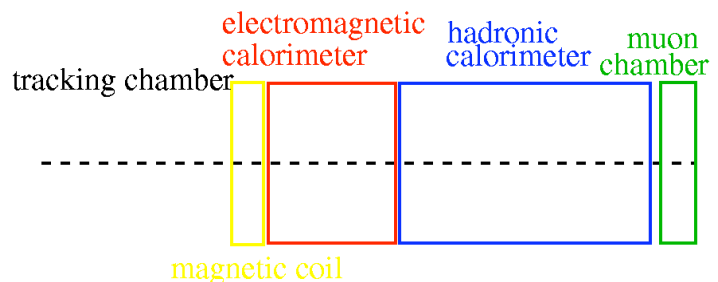
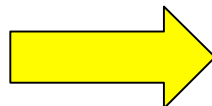
- Taus:

- Narrow jet
- Matched to one or three tracks



- Neutrinos:

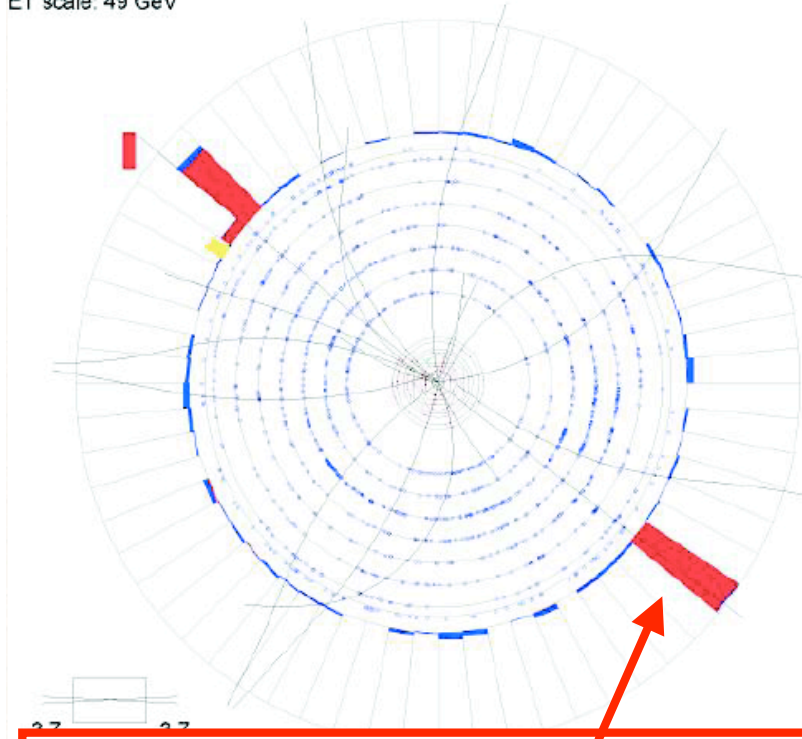
- Imbalance in transverse momentum
- Inferred from total transverse energy measured in detector
- More on this in Lecture 4



Electrons and Jets

Run 166892 Evt 2775140 Sun Oct 27 03:15:49 2002

ET scale: 49 GeV

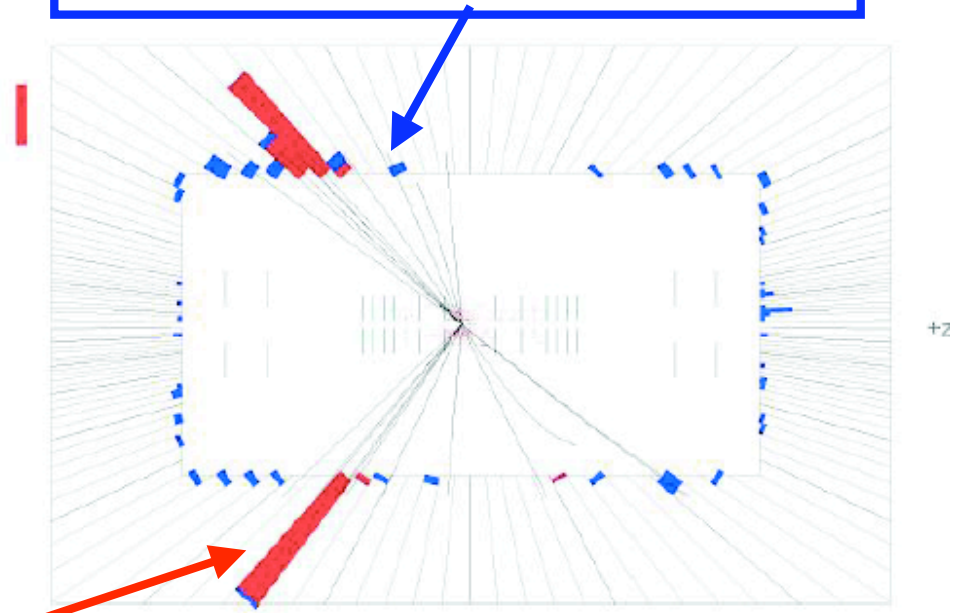


Electromagnetic Calorimeter Energy

Run 166892 Evt 3223863 Sun Oct 27 03:43:08 2002

E scale: 20 GeV

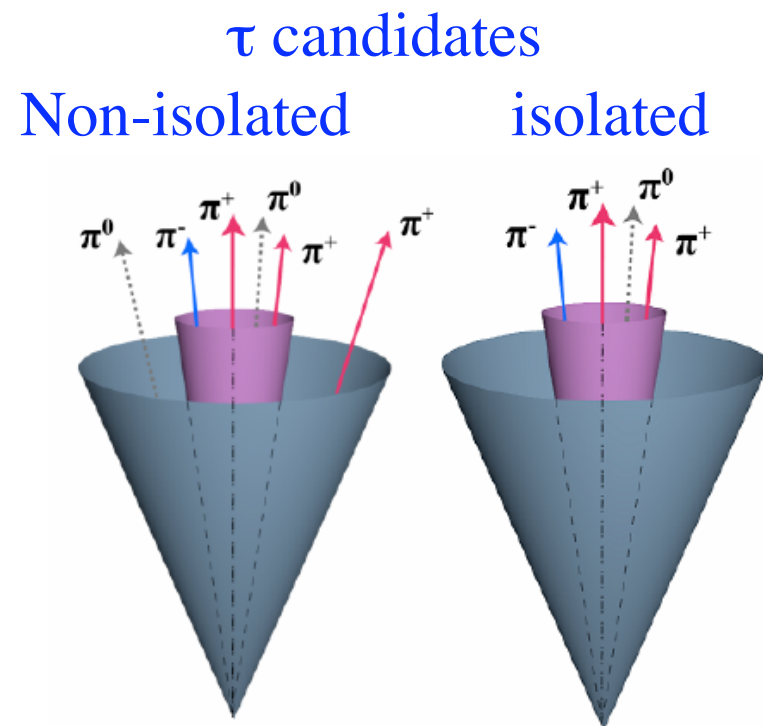
Hadronic Calorimeter Energy



- Jets can look like electrons, e.g.:
 - photon conversions from π^0 's: ~13% of photons convert (in CDF)
 - early showering charged pions
- And there are lots of jets!!!

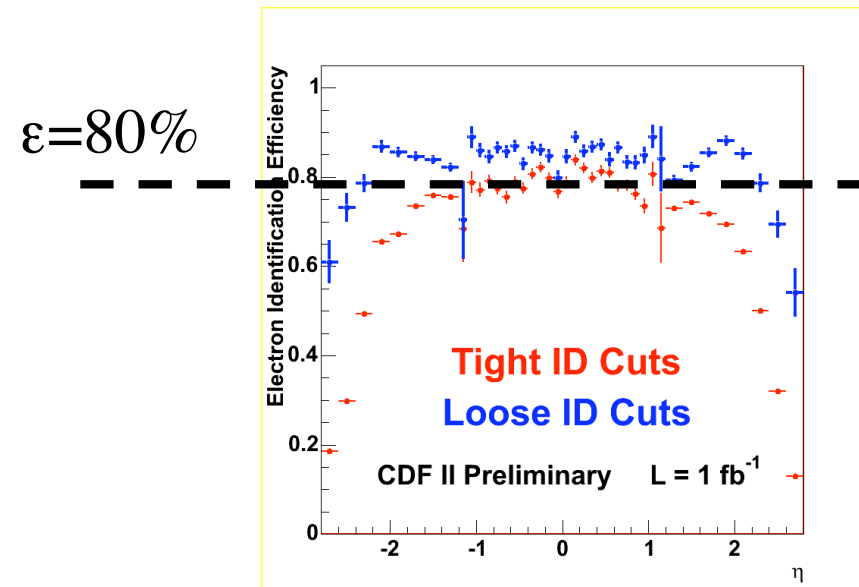
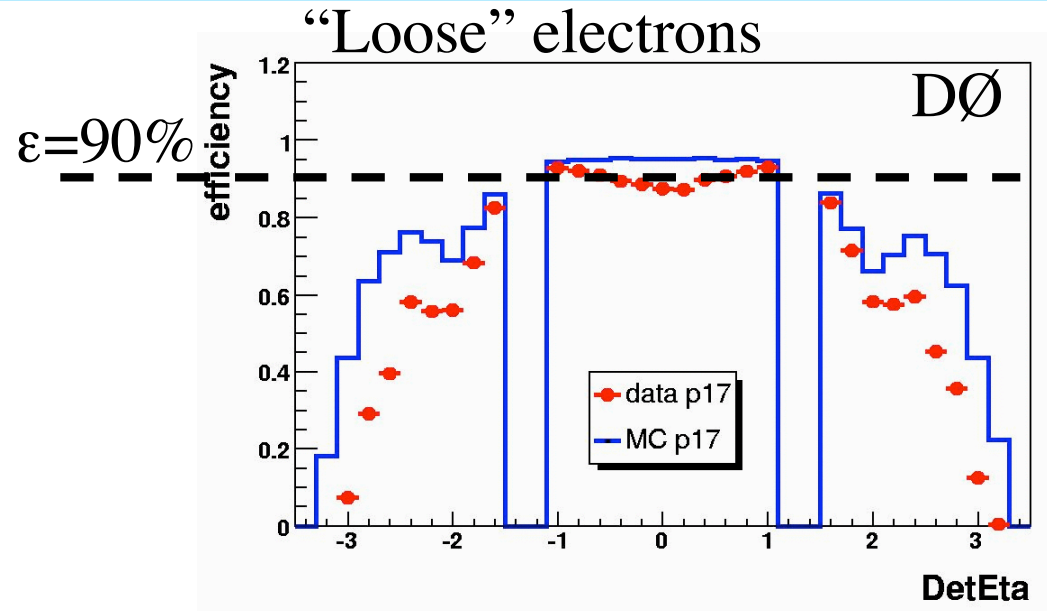
The Isolation Cut

- Isolation is very powerful for isolated leptons
 - E.g. from W's, Z's
- Rejects background from leptons inside jets due to:
 - b-decays
 - photon conversions
 - pions/kaons that punch through or decay in flight
 - pions that shower only in EM calorimeter
- This is a physics cut!
 - Efficiency depends on physics process
 - The more jet activity the less efficient
 - Depends on luminosity
 - Extra interactions due to pileup
- Isolation cut:
 - Draw cone of size 0.4 around object
 - Sum up P_T of objects inside cone
 - Use calorimeter or tracks
 - Typical cuts:
 - $<10\% \times E_T$
 - $<2-4 \text{ GeV}$



Electron Identification

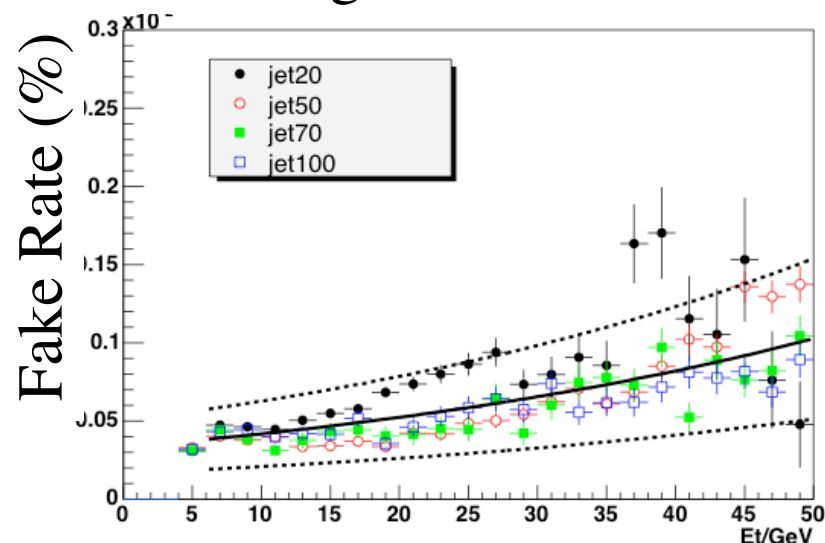
- Desire:
 - High efficiency for isolated electrons
 - Low misidentification of jets
- Cuts:
 - Shower shape
 - Low hadronic energy
 - Track requirement
 - Isolation
- Performance:
 - Efficiency:
 - Loose cuts: 86%
 - Tight cuts: 80%
 - Measured using Z's
 - Fall-off in forward region due to limited tracking efficiency



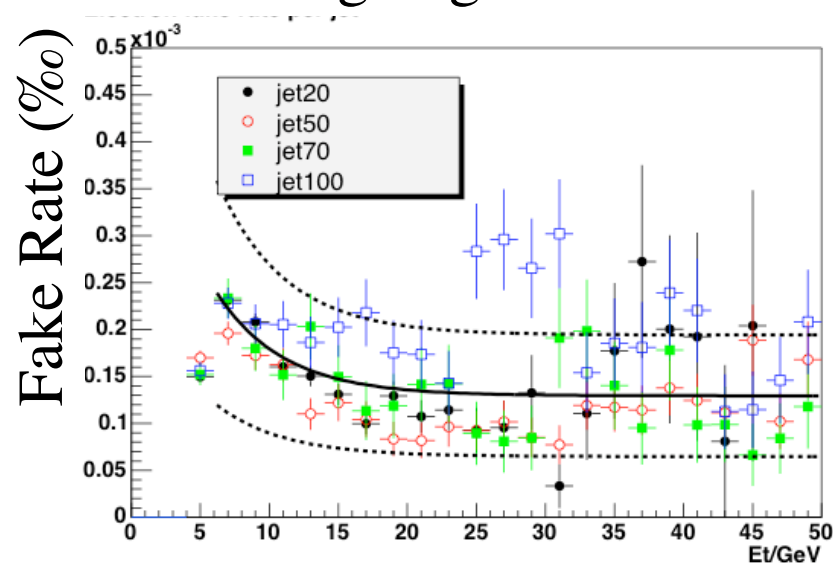
Jets faking Electrons

- Jets can pass electron ID cuts,
 - Mostly due to
 - early showering charged pions
 - Conversions: $\pi^0 \rightarrow \gamma\gamma \rightarrow ee + X$
 - Semileptonic b-decays
 - Difficult to model in MC
 - Hard fragmentation
 - Detailed simulation of calorimeter and tracking volume
- Measured in inclusive jet data at various E_T thresholds
 - Prompt electron content negligible
 - Fake rate per jet:
 - Loose cuts: 5/100000
 - Tight cuts: 1/100000
 - Typical uncertainties 50%

Jets faking “loose” electrons



Jets faking “tight” electrons



W's and Z's

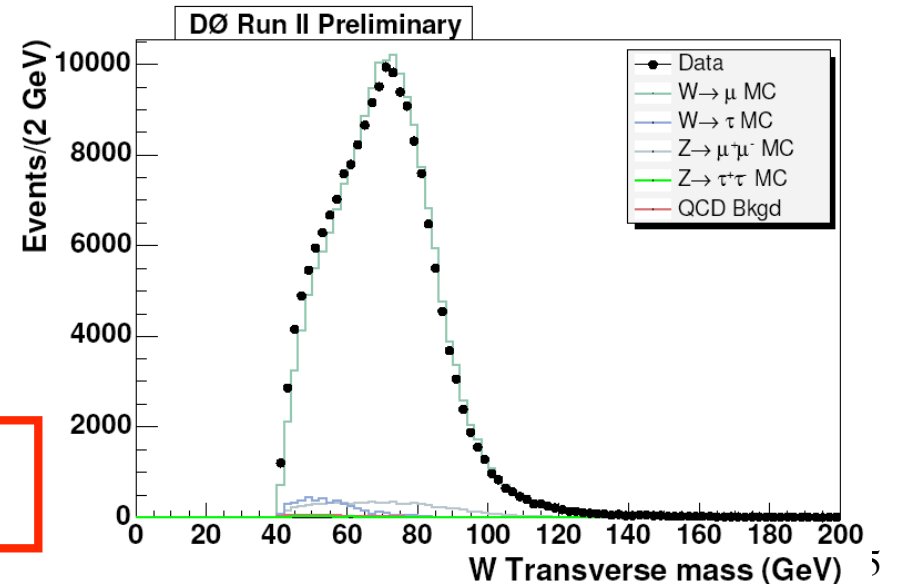
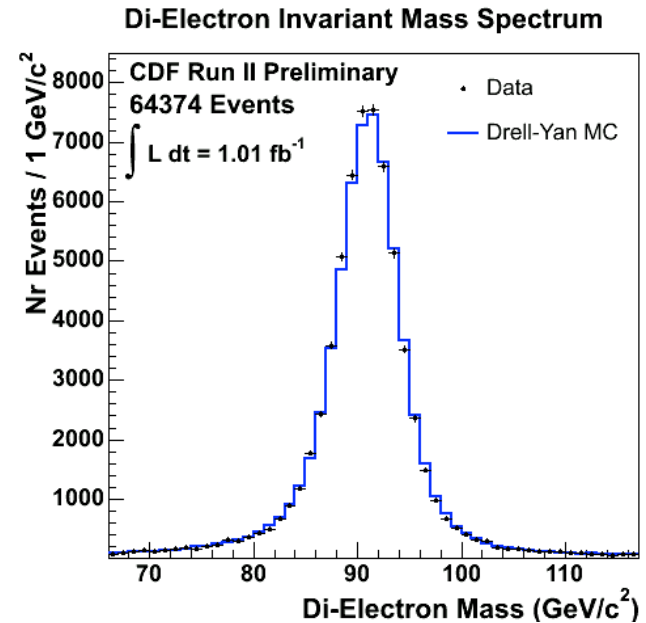
- **Z** mass reconstruction
 - Invariant mass of two leptons

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

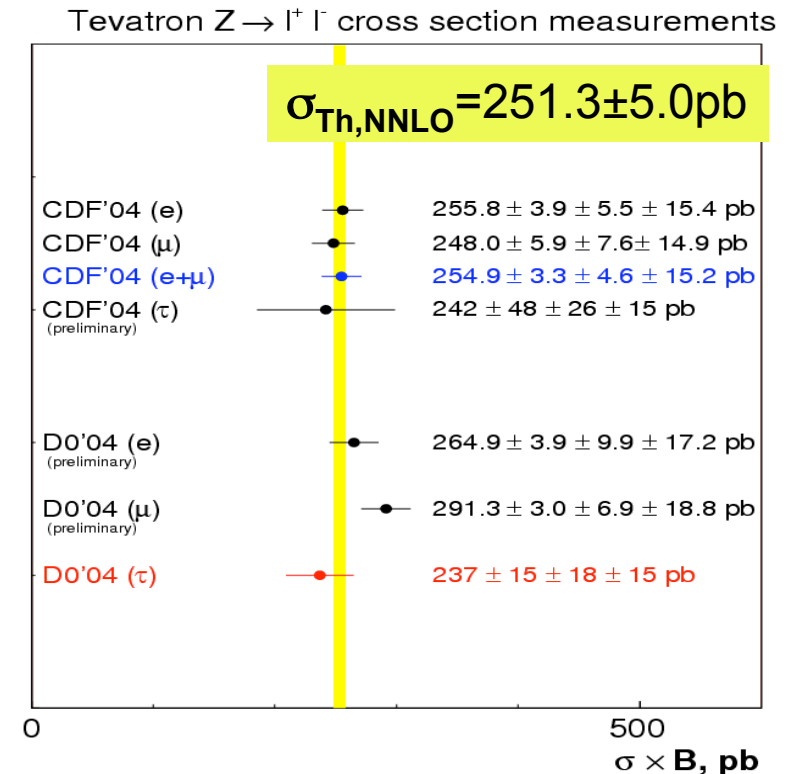
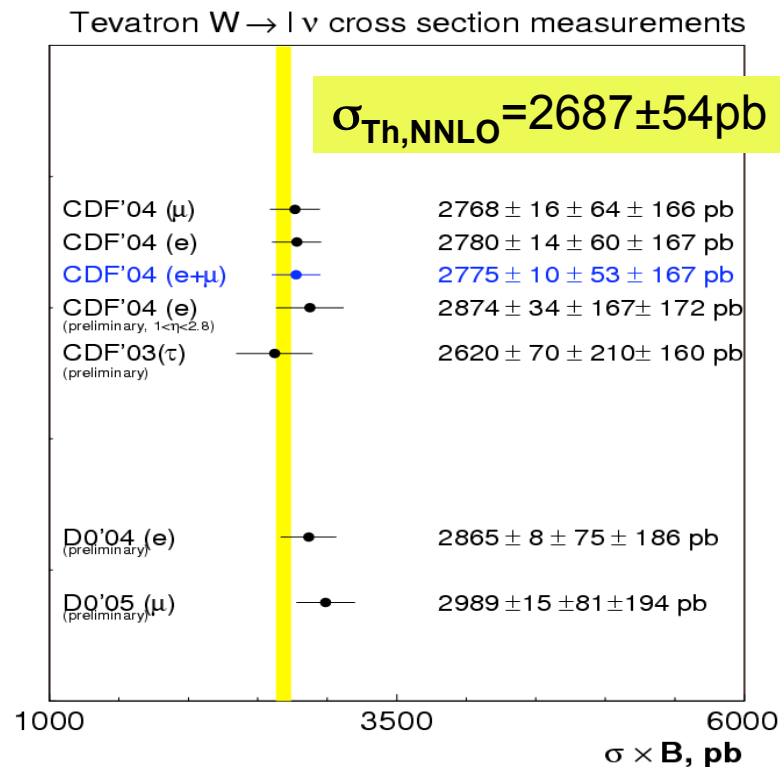
- Sets electron energy scale by comparison to LEP measured value

- **W** mass reconstruction
 - Do not know neutrino p_z
 - No full mass reconstruction possible
 - Transverse mass:

$$m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2}$$

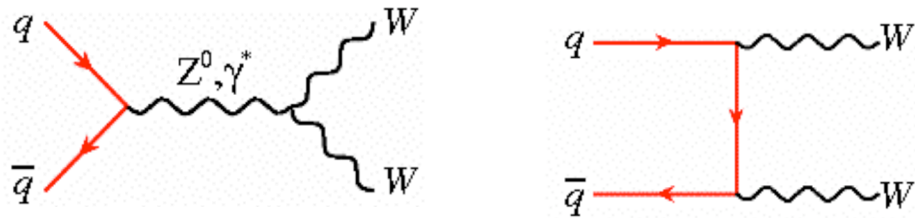


Cross Section Results

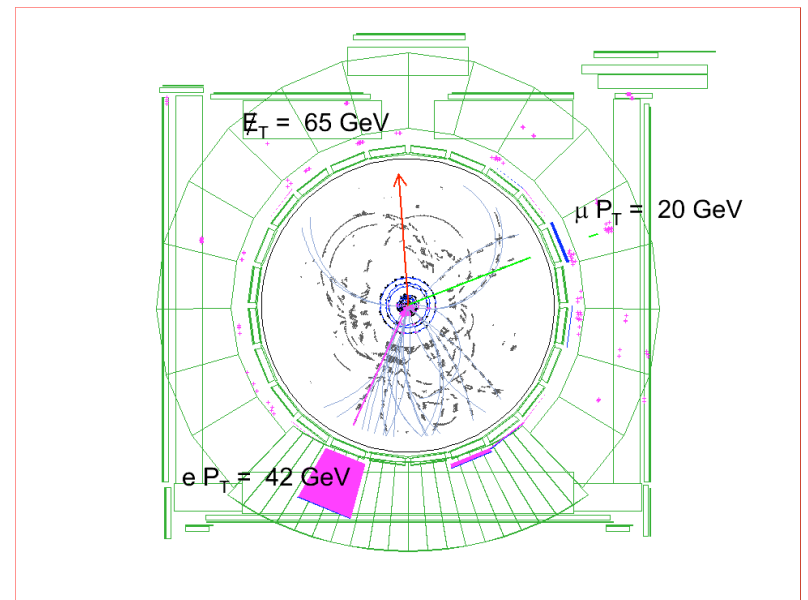
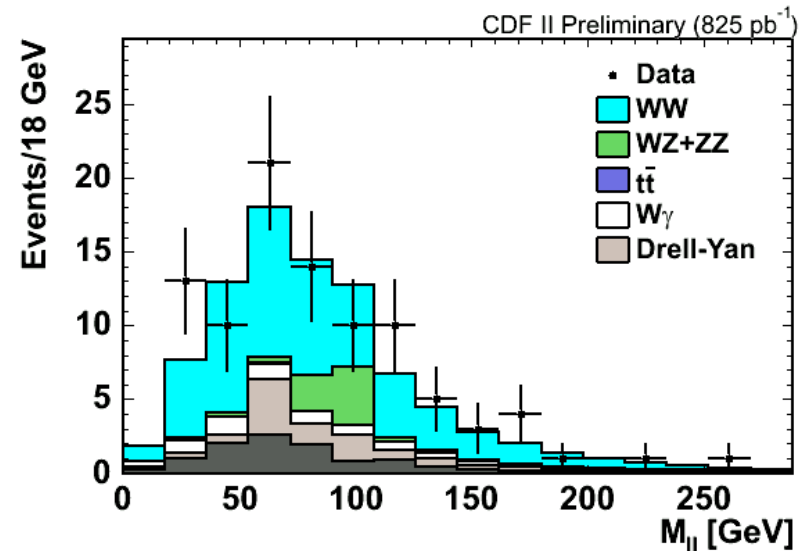


- Excellent agreement with NNLO QCD calculations
- Dominant uncertainty is due to luminosity uncertainty: $\sim 6\%$
- Theoretical uncertainty on W and Z cross section: $\sim 2\%$
- Can use W's and Z's to set absolute luminosity normalisation

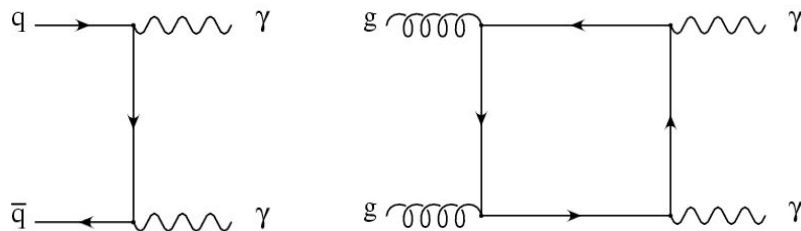
WW Cross Section



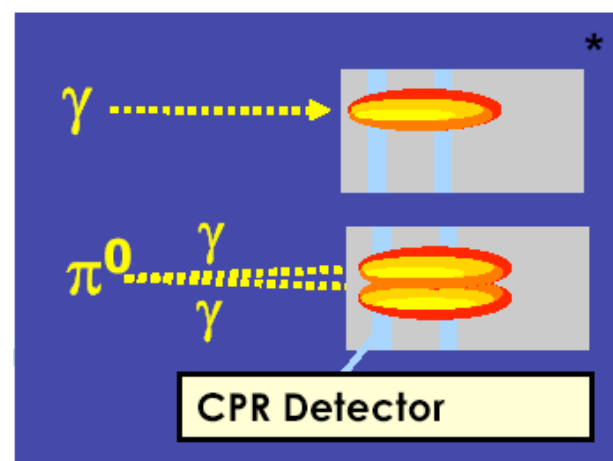
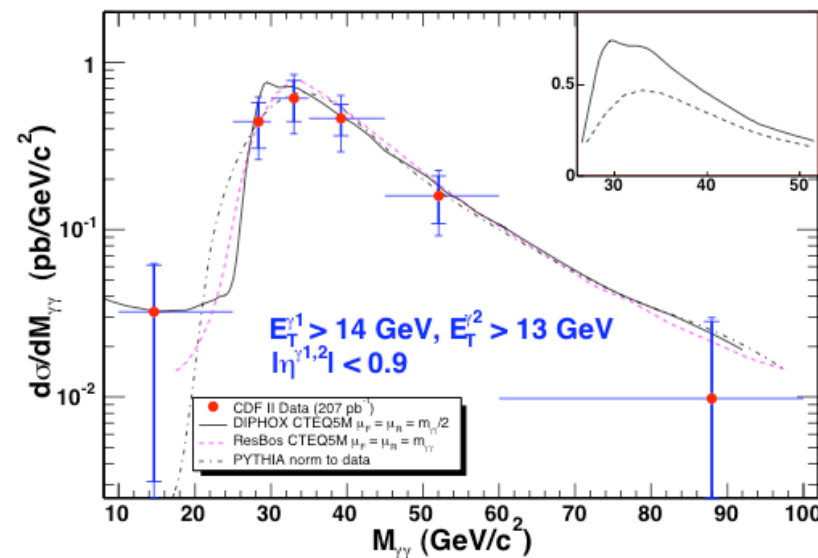
- WW cross section
 - Use $W \rightarrow \mu \nu$ and $W \rightarrow e \nu$
 - 2 leptons and missing E_T
- Result:
 - Data: $\sigma = 13.6 \pm 3.1$ pb
 - Theory: $\sigma = 12.4 \pm 0.8$ pb
 - Campbell, Ellis



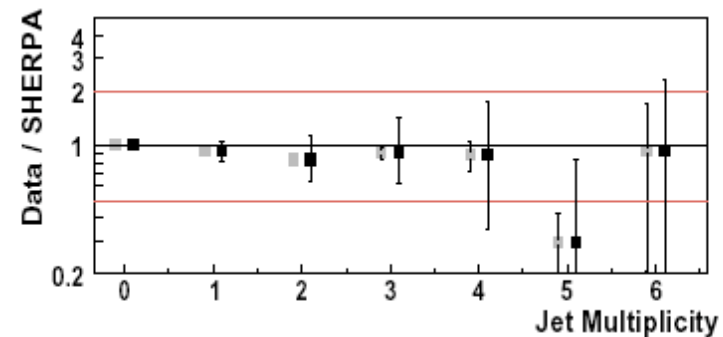
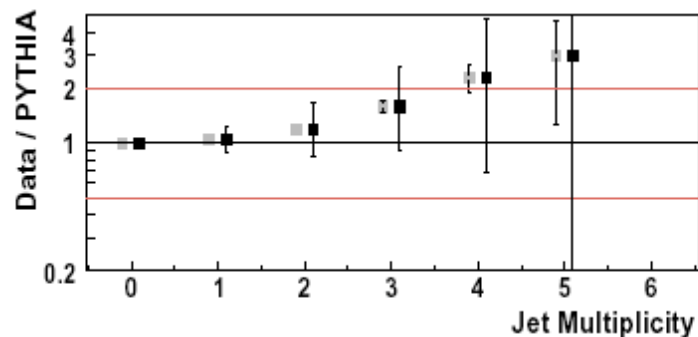
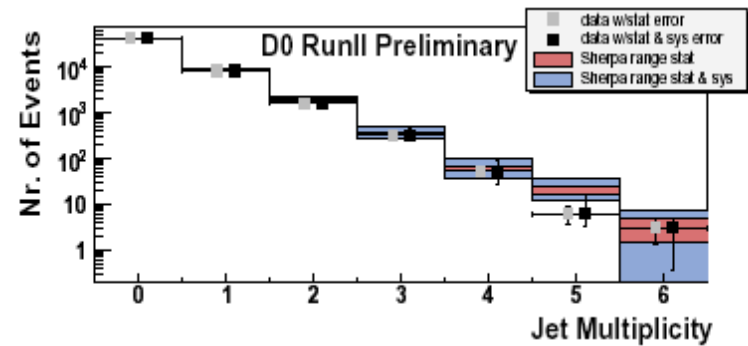
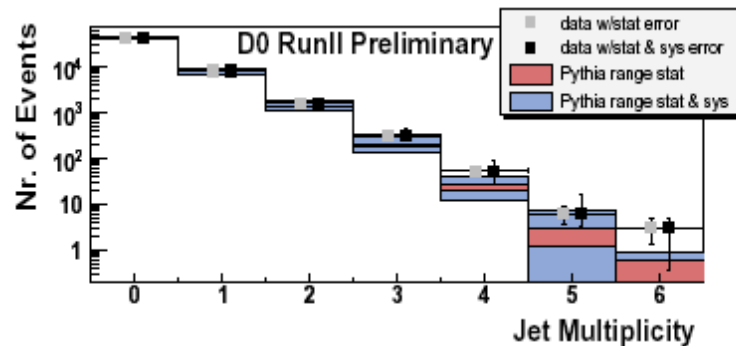
Diphoton Cross Section



- Select 2 photons with $E_T > 13$ (14) GeV
- Statistical subtraction of background
 - mostly $\pi^0 \rightarrow \gamma\gamma$
- Data agree well with NLO
- PYTHIA describes shape
 - normalization off by factor two



Z+jet Cross Section



- Select Z boson and jets
- Compare MC generators PYTHIA and SHERPA
- SHERPA gives better description

Conclusion

- Tevatron is world's highest energy collider today
 - Large datasets with $L=1.5 \text{ fb}^{-1}$ now available in Run II
 - 10 times more statistics than in Run I
 - CDF and DØ detectors operate well
 - Powerful tracking
 - Good calorimeter coverage
 - Good lepton identification
- A hadron machine provides a challenging environment
 - Cross sections of jets, W's and Z's and other processes at $\sqrt{s}=1.96 \text{ TeV}$ well understood
 - Excellent agreement with QCD calculations
 - This is important before moving on to rarer processes, precision measurements and new physics searches
 - See the next 3 lectures!

